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STRESS CORROSION CRACKING MECHANISMS IN MARTENSITIC HIGH STRENGTH STEELS

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TRW Inc.

TECHNICAL REPORT AFML-TR-67-98
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AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

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The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, Air Force Systems Command, Wright Patterson Air Force Base, Ohio, with Howard Middendorp (MAMP) acting as project engineer.

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This technical report has been reviewed and is approved.

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ABSTRACT

Delayed failures of martensitic high-strength steels in aqueous environments were studied to determine the effect of environmental and metallurgical variables on the mechanism(s) of stress corrosion. The effects of chloride content, specimen geometry, and polarization potential on the delayed failure of AISI 4340 (235 and 207 Ksi strength level) and HP 9-4-45 (242 Ksi strength level)steels were evaluated. Incubation time for slow crack growth and crack growth rates were measured at various combinations of applied stress and environment using change of resistance and compliance measurements on precracked center-notch tensile and cantilever loaded notch bend specimens.

No basic difference in environmentally-induced failure mechanism due to type of loading (plane stress versus plane strain) was found for either material. In addition, a critical stress intensity parameter (K_{ISCC}) was defined below which stress corrosion was not observed.

In 4340 steel the variation of incubation time for initiation of slow crack growth with changes in the sequence of aging under load with and without an environment was consistent with a concept that a film,which formed at the at the crack tip between the precracking and testing operations, controlled the incubation behavior. The crack growth rates and the time to failure after slow crack growth was initiated were not affected by changes in the aging sequence.

Results of polarization experiments indicated that delayed failure in 4340 steel is consistent with a hydrogen embrittlement mechanism. The behavior of the HP 9-4-45 steel however was consistent with a concept of anodic dissolution along active paths. These differences suggest that one general mechanism of delayed failure in aqueous environments is not applicable to all classes of high-strength steels.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Cross sectional area
A_i	Initial cross sectional area
A_{i2}	Reduced cross sectional area (anodic polarization studies)
B	Specimen thickness
CN	Center notched
D	Specimen depth (NB tests)
E	Young's modulus
K	Stress intensity parameter
K_i	Applied stress intensity parameter
K_c	Stress intensity parameter at fracture in air
K_{cf}	Stress intensity parameter at fracture (stress corrosion tests)
K_{IC}	Plane strain fracture toughness (stress intensity parameter at fracture in air under plane strain conditions)
M	Applied moment
NB	Notch bend
P	Applied load
R	Electrical resistance
ΔR	Resistance change
V_I	Impressed electrical potential
V_N	Natural potential of steel-environment interface
W	Specimen width (sheet tensile and CN tests)
a	Crack length
a_o	Initial crack length ($2a_o$ in CN tests)

a_f	Final crack length ($2a_f$ in CN tests)
t	Time
t_i	Incubation time
t_f	Failure time
v	Specimen compliance
α	$1 - \frac{a}{D}$ (NB specimens)
σ	Stress
σ_a	Applied stress
σ_{NTS}	Notch tensile strength
σ_{UTS}	Ultimate tensile strength
σ_y	Yield stress (0.2% offset)
da/dt	Crack growth rate

SECTION I

INTRODUCTION

The ability of specific environments to degrade the load carrying capability of structural materials has long been recognized. Of prime concern are those materials which are susceptible to failure at stresses considerably below their design strength when exposed to normal operating environments. For example, certain martensitic high strength steels containing a notch can fail within 10 minutes at 20% of the yield strength and 50% of the notch tensile strength when in contact with an aqueous environment (1)*.

Although embrittlement due to aqueous environments has been well documented, there is still controversy concerning the mechanism(s) by which delayed failure occurs. Mechanistic studies in this area are difficult since the environment effects are often confounded by the complexities of normal fracture behavior. However, improvement in the methods of analyzing fracture through the use of linear elastic fracture mechanics allows the fracture process to be studied on a macroscopic basis independent of the influence of specimen geometry effects. A definition of the events which contribute to fracture, independent of environment, must serve as the logical framework for understanding the process of environmentally-induced fracture in martensitic high strength steels.

The object of this program is to investigate the fundamental factors which control environmentally-induced delayed failure in high strength steels. The study is divided into two phases: 1) the influence of environmental variables and, 2) the influence of metallurgical variables on the delayed failure characteristics of martensitic steels.

Environmentally-induced failures are characterized by a decreased failure time accompanying an increased stress level. Results obtained on a high strength steel exposed to distilled water (1) illustrate the stress dependent failure time, as well as the fact that a finite incubation time is required before crack growth commences. Although not firmly established, there also appears to be a threshold stress level below which no stress corrosion cracking is observed.

Stress corrosion type failure of a particular metal occurs only in specific environments and in most cases negligible material loss by gross corrosion is incurred. The normal sequence of events leading to stress corrosion failure is:

1) the metal surface becomes pitted by nonuniform corrosion,

2) a crack emanates from the pit and undergoes slow growth,

---

* Numbers in parentheses pertain to references listed on page 54.

3) the crack reaches a critical size and the remaining metal ligament ruptures by purely mechanical fracture.

The stress corrosion characteristics of high-strength steels have been intimately connected with the material's fracture toughness (2). If a steel is tested above its ductile-to-brittle transition temperature, environmentally-induced slow crack growth occurs over a relatively large distance before catastrophic failure occurs. When tested below the transition temperature, significantly less slow crack growth would be observed before total failure. The tougher steel may actually have an environmentally-inducted crack growth rate which is greater than that of a brittle steel, but the time-to-failure parameter would mask the effect and indicate that the brittle steel is more susceptible.

The experiments conducted in this program are designed to reveal differences in crack growth behavior which then may be related to environmental or metallurgical variables. In addition, extensive use is made of fracture mechanics analyses to describe the material loading condition and thus separate the stress-corrosion effects from those of purely mechanical fracture.

SECTION II

MATERIALS AND TEST PROCEDURES

AISI 4340 and HP 9-4-45 are the high strength steels being used to study the influence of environment on delayed failure characteristics. Both materials were examined in 0.050 inch sheet and 1 inch plate at approximately the 235 Ksi tensile strength level while only the AISI 4340 sheet material was evaluated at the 207 Ksi level. The chemical compositions of the materials are shown in Table 1 while the tensile properties and heat treatments are given in Table 2.

The geometry of the smooth sheet, the precracked sheet, and the precracked beam specimens are shown in Figures 1 through 4. All sheet specimens had a minimum of 0.005 inch ground from each surface after heat treatment to remove the slight decarburized layer (0.003 to 0.005 inch) detected by a Knoop hardness traverse on a cross section of heat treated AISI 4340 sheet. All specimens were given a finish grind with 100 grit paper with the grinding marks parallel to the loading direction. Precracking was performed after heat treatment at stresses which provided the desired crack size in 15,000 to 50,000 cycles (3). After precracking, all specimens were cleaned with acetone and stored in a vacuum dessicator until tested. The sustained load tests of sheet specimens were conducted on self-leveling, lever-loaded creep rupture racks while the cantilever beam specimens were stressed by means of a simple beam extension lever and appropriate weights.

Delayed failure tests were conducted in distilled water and in 1.5N and 3.0N NaCl aqueous solutions. Environments were applied by attaching a plexiglass-neoprene container to the specimen and then filling the container with the desired media. In the case of the smooth tensile specimens, the entire gauge length was submerged while only the specimen area in the vicinity of the crack was exposed on the precracked specimens. Unless otherwise specified, the environment was applied immediately before the application of the load.

Crack initiation and growth characteristics of precracked specimens were monitored by two methods: electrical resistance measurements and displacement gauge measurements. The technique of measuring electrical resistance changes which has been described previously (4,5) involves making the specimen one leg of a Kelvin-Wheatstone double bridge and measuring the increase in resistance which accompanies crack extension. The apparatus, schematically shown in Figure 5, is capable of detecting crack growth extensions greater than approximately 0.005 inch

The displacement gauge technique is illustrated in Figure 6 and consists of measuring the change in specimen compliance as the stress corrosion crack grows. The technique is similar to those discussed by Brown and Srawley (6,7) except that the span (gauge length) over which the compliance is measured is 3-1/4 inches so that the environment chamber can be accommodated. The sensitivity to crack extension is approximately the same as for the resistance change technique.

TABLE 1

CHEMICAL COMPOSITION OF TEST MATERIALS

Steel	Vendor	Heat	Thkns.(in.)	Composition (Wt. Percent)										
				C	Mn	Si	Cr	Mo	Ni	P	S	Co	V	Fe
4340	Vasco	09897	0.065	0.35	0.60	0.25	0.72	0.27	1.85	0.010	0.006	--	--	Bal
4340	Vasco	08290	1	0.43	0.69	0.31	0.81	0.28	1.83	0.010	0.004	--	--	Bal
HP 9-4	Republic	3921091	0.060	0.43	0.15	0.01	0.32	0.30	7.80	0.006	0.009	3.95	0.09	Bal
HP 9-4	Republic	3921091	1	0.43	0.15	0.01	0.32	0.30	7.80	0.006	0.009	3.95	0.09	Bal

TABLE 2

TENSILE PROPERTIES AND HEAT TREATMENTS FOR TEST MATERIALS

Steel	Heat Treatment	U.T.S.	0.2% Y.S.	% Elong.	% Red. Area
4340 Sheet	Normalize at 1700°F for 15 min. in salt, AC, austenitize at 1550°F for 15 min. in salt, OQ, Temper 500°F - 1 hour, plus 500°F - 1 hour.	238.2 235.3	201.0 200.1	8.5 8.0	--- ---
	Temper 700°F - 1 hour, plus 700°F - 1 hour.	205.2 209.5	189.2 192.5	7.0 6.5	--- ---
4340 Plate	Normalize at 1700°F for 1 hour in salt, AC, austenitize at 1550°F for 1 hour in salt, OQ. Temper 725°F - 1 hour, plus 725°F - 1 hour.	229.9	202.9	14.5	55.6
HP 9-4 Sheet	Four hours at 1200°F., four hours at 1300°F in argon atmos., AC. Austenitize at 1450°F for 15 min., OQ. Temper 2-1/4 hours at 650°F.	242.4	222.9	8.5	---
HP 9-4 Plate	Four hours at 1200°F., four hours at 1300°F., in argon atmos., AC. Austenitize at 1450°F for 1 hour, OQ. Temper 2-1/4 hours at 650°F.	243.6 240.1	219.5 213.1	11.0 11.0	41.3 34.7

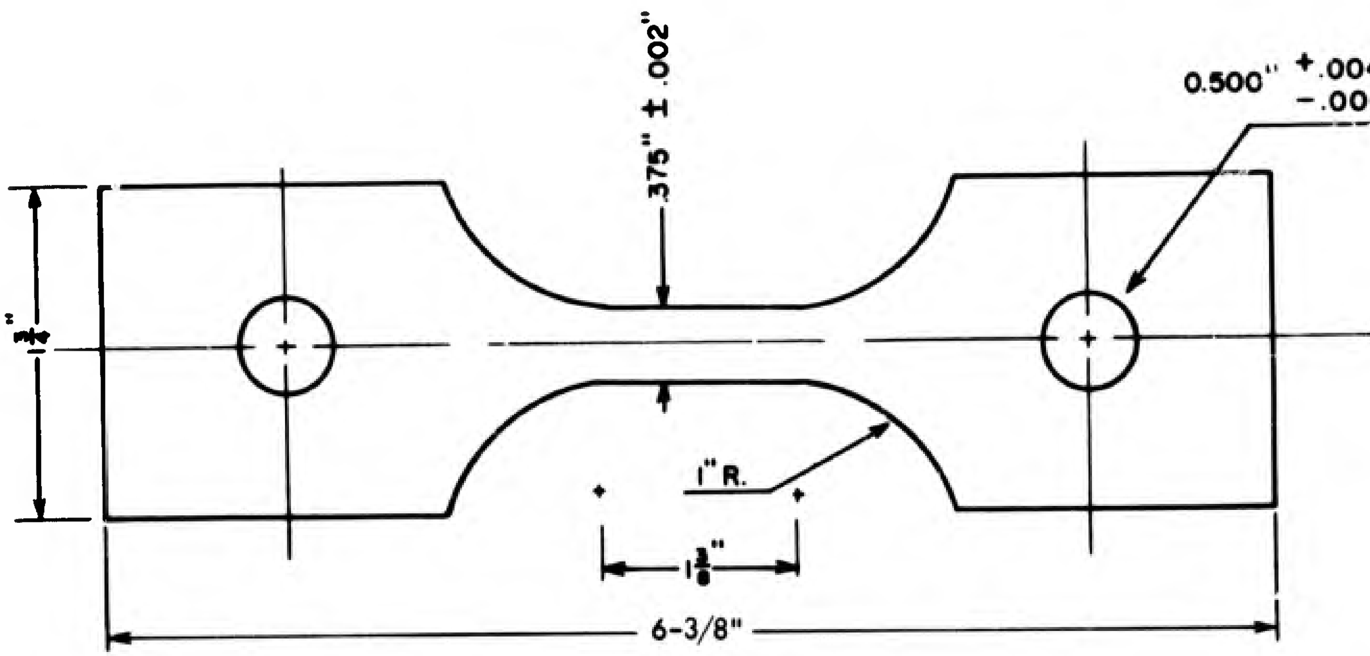


Figure 1. Smooth Sheet Tensile Specimen.

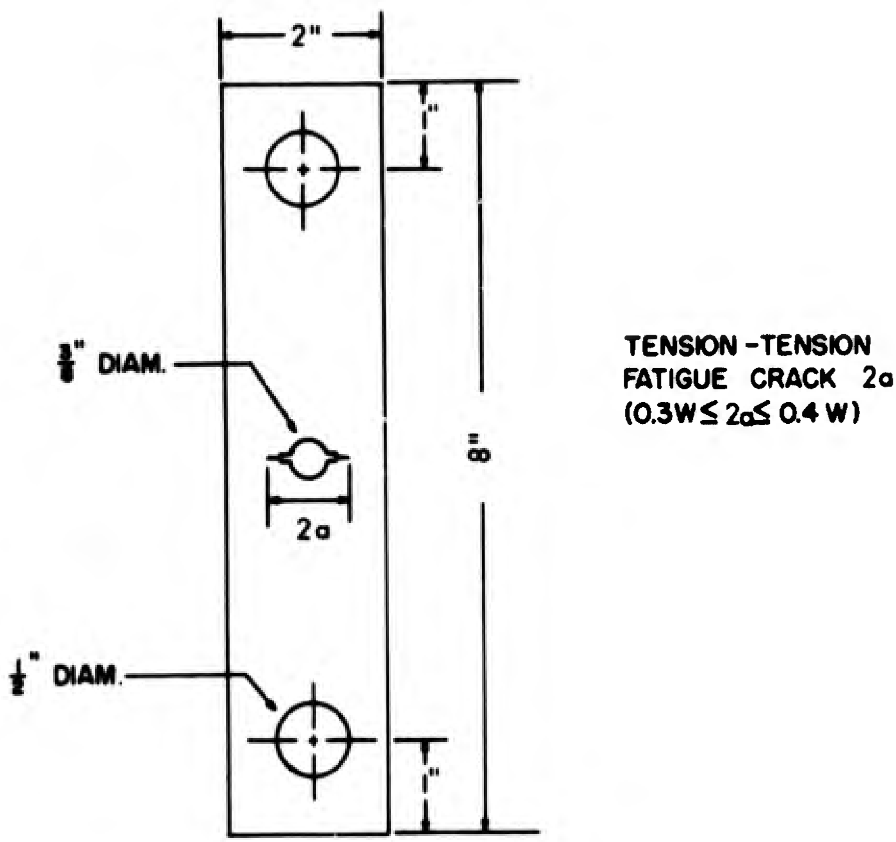


Figure 2. Center-Notch Specimen Geometry for AISI 4340 Steel.

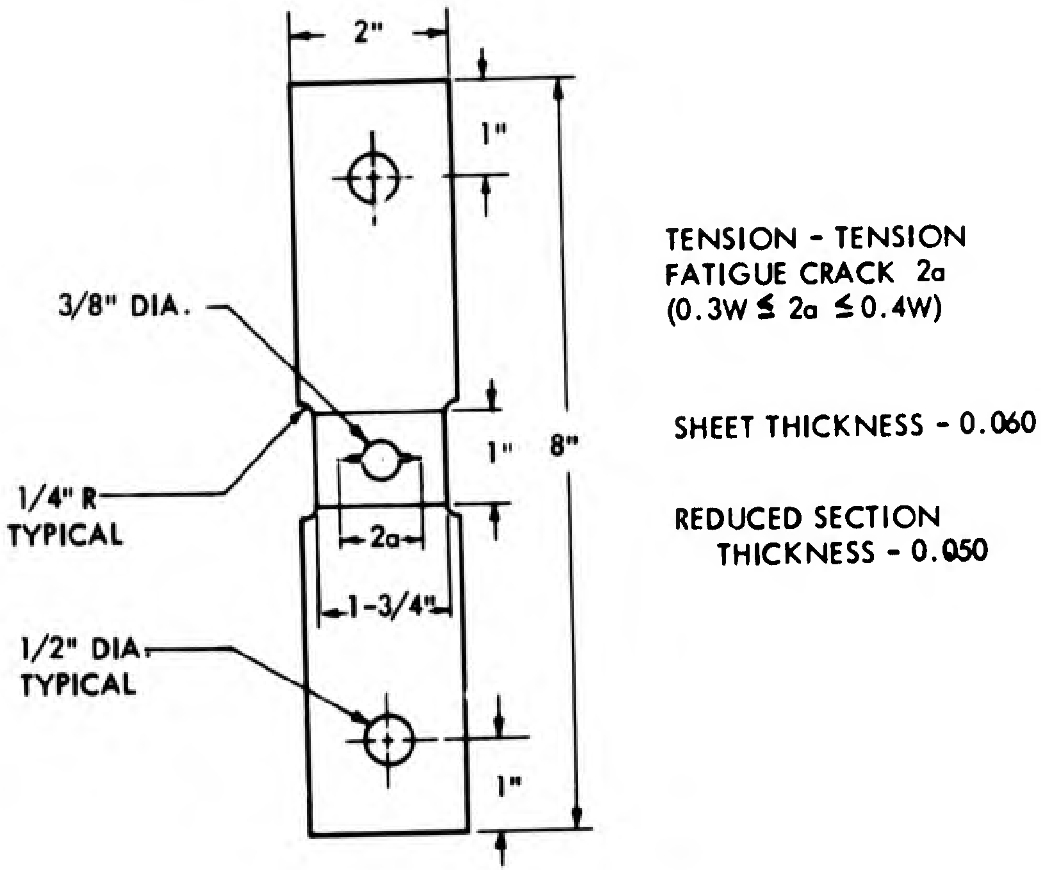


Figure 3. Center-Notch Specimen Geometry for HP 9-4-45 Steel.

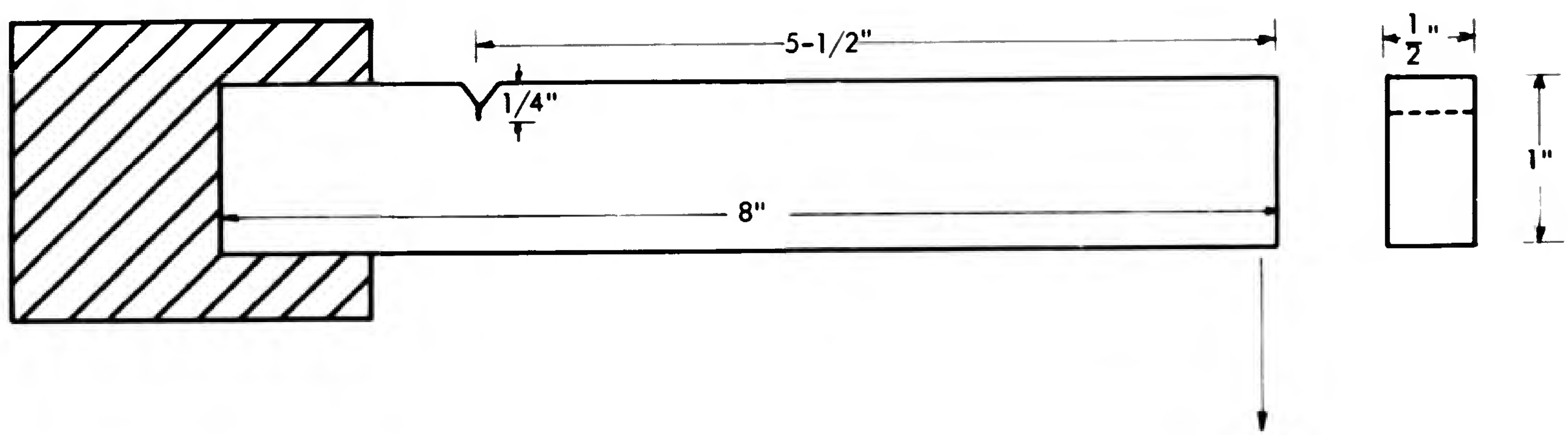


Figure 4. Cantilever Beam Specimen Geometry.

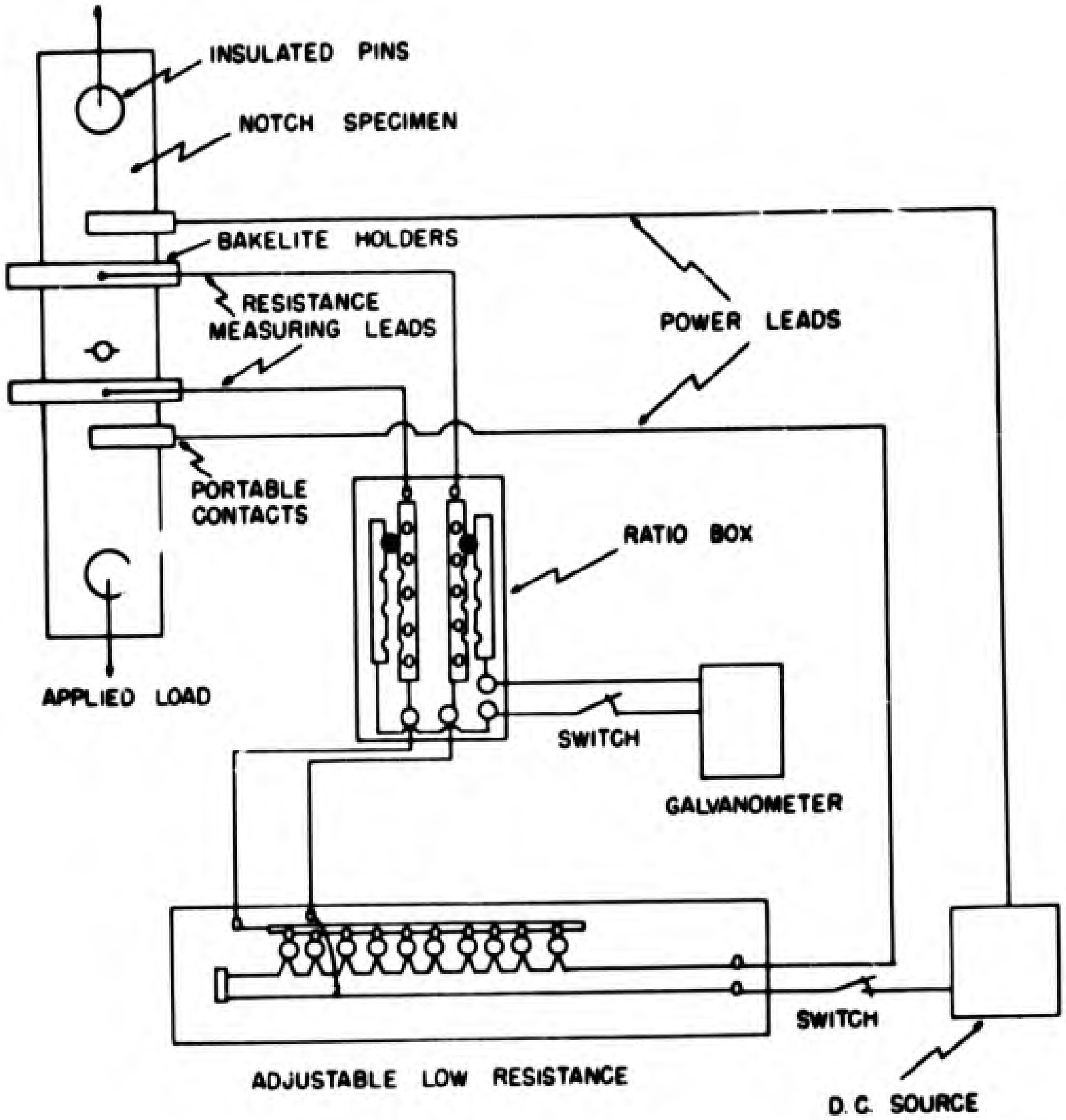


Figure 5. Schematic Diagram of Resistance Apparatus Used to Study Crack Initiation and Growth Characteristics.

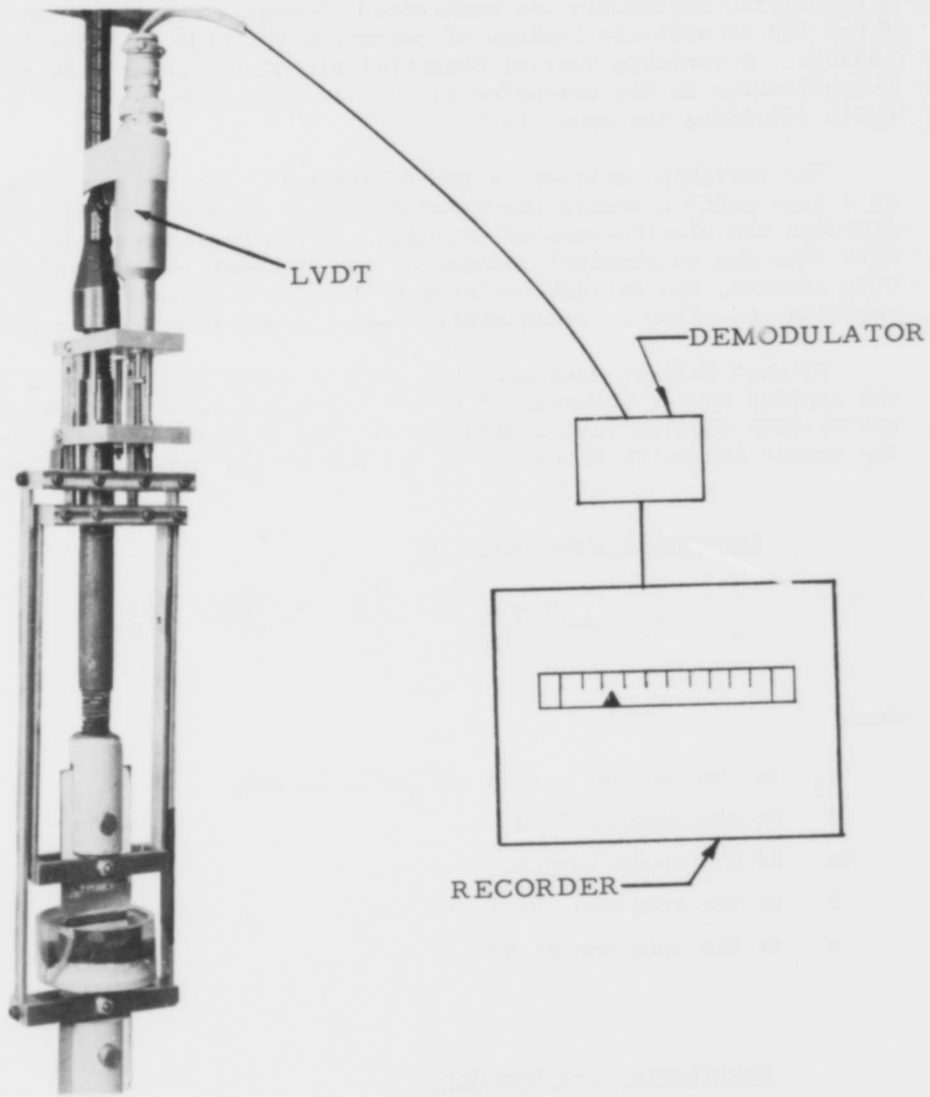


Figure 6. Illustration of Compliance Gauge Method of Recording Crack Extension.

The effect of an impressed polarization potential on delayed failures was conducted on center-notched sheet specimens using the electrical circuitry shown in Figure 7. Standard dry cells provided the polarizing power. The solution potential was measured against a saturated potassium chloride calomel electrode. Electrolytic continuity was maintained through a capillary tube with an asbestos fiber tip to minimize leakage of potassium chloride solution into the environment chamber. A variable bucking potential placed in series with the 0-100 millivolt potentiometer in the measuring circuit increased the range of the potentiometer while retaining its sensitivity.

The variable resistor in the polarization circuit was adjusted at the start of a test until a stable impressed potential of the desired value was reached. Although the electrochemical potential of the specimen surface undergoes changes with time due to chemical changes at the specimen surface and electrode polarization effects, the initial resistor settings were maintained to provide a reference position and allow a semiquantitative interpretation of the polarization effects.

Delayed failure data are presented in terms of both notch tensile strength and applied stress intensity factor. The notch tensile strength is defined as the maximum applied load divided by the net specimen area for fracture in air. The stress intensity factors (K_i) are determined from the following formulae:

Precracked Sheet Specimen

$$K_i = \frac{1.77\,P\sqrt{a}}{BW}\left[1 - 0.1\left(\frac{2a}{W}\right) + \left(\frac{2a}{W}\right)^2\right] \qquad \text{(Equation 1)}$$

where

K_i is the applied stress intensity factor,

P is the applied load,

2a is the crack length,

B is the specimen thickness and,

W is the specimen width.

Cantilever Beam Specimen

$$K_i = \frac{4.12M\sqrt{\frac{1}{\alpha^3} - \alpha^3}}{BD^{3/2}} \qquad \text{(Equation 2)}$$

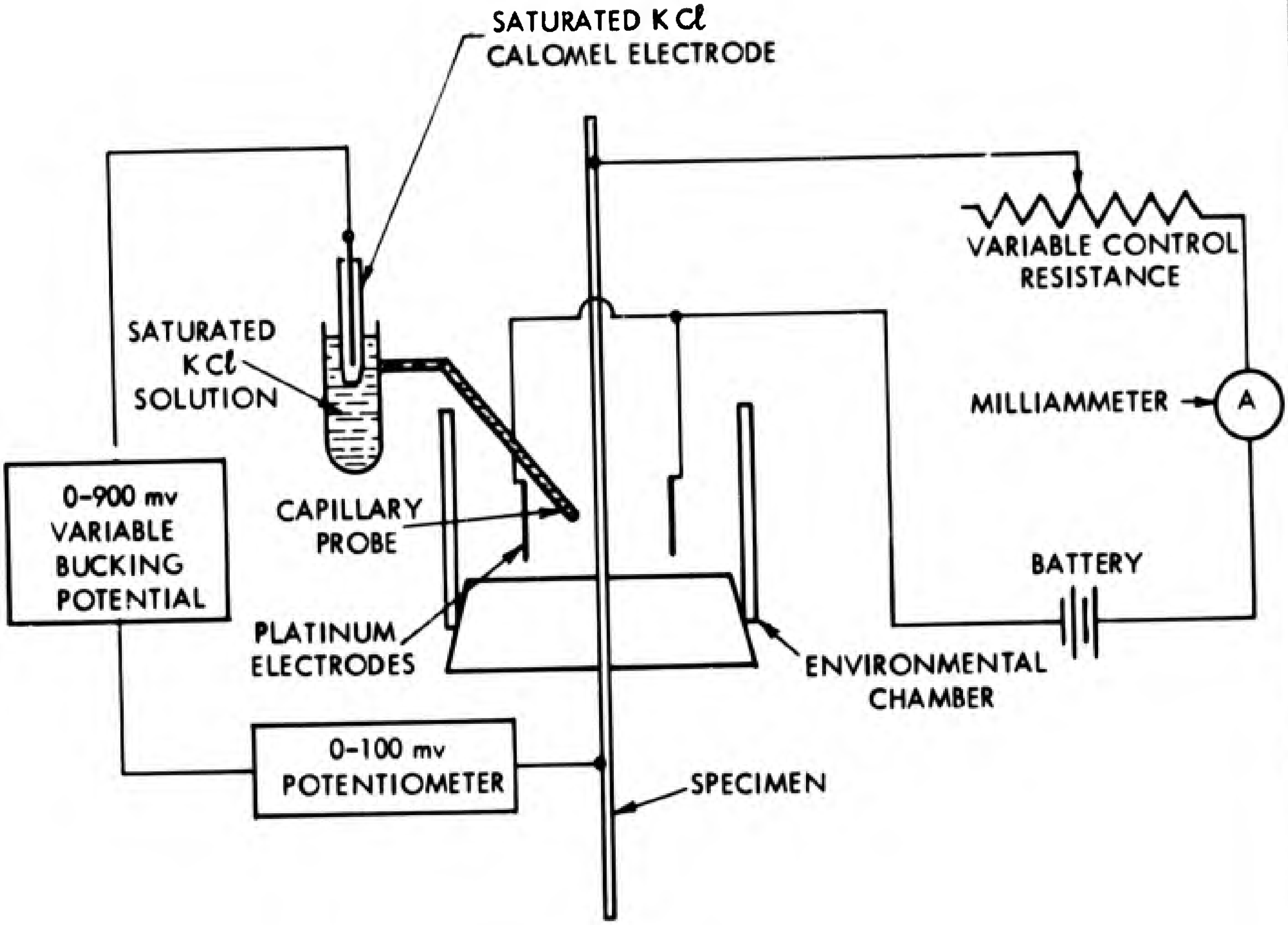


Figure 7. Circuit Diagram for Polarization Studies.

where

K_i is the applied stress intensity factor,

M is the applied moment,

B is the specimen thickness,

D is the specimen depth,

α is (1-a/D) where a is the crack length.

The K_i values for precracked sheet specimens (Equation 1) were determined by computer calculation.

SECTION III

RESULTS AND DISCUSSION

In the first phase of the program, dealyed failure in two high strength martensitic steels was studied by systematically varying test environments. The initial set of experiments involved exposing smooth tensile, center-notch tensile and cantilever loaded notch bend specimens to distilled water and two NaCl aqueous solutions and determining an applied stress versus failure time curve for each system.

A comparison of the smooth and precracked center-notch sheet tensile specimen results was made to reveal the contribution of the pitting or crack formation stage to the total failure process. Comparison of the center-notch sheet and notch bend data indicated whether the stress state (plane stress versus plane strain) influences the environmentally-induced crack growth rate.

This portion of the report contains the results of several series of stress corrosion experiments presented predominantly in graphical form to show the influence of environmental variables and specimen geometry on the stress corrosion process. The specific test data are summarized in the Appendix.

1. Delayed Failure of AISI 4340 Steel

Delayed failure in precracked AISI 4340 steel specimens was produced as low as 20% of the notch tensile strength, regardless of specimen geometry or environment. The following paragraphs discuss the effect of chloride content, geometry, and strength level on the delayed failure process in 4340 steel.

A. Influence of Environment - Distilled water and 1.5N and 3.0N NaCl aqueous environments were applied at room ambient temperature to fatigue precracked center-notch tensile specimens under sustained load. The presence of the fatigue precrack eliminates the pitting and crack formation stages of stress corrosion and under these conditions, delayed failures occurred for both strength levels of the 4340 steel in contact with all media. Figures 8 and 9 summarize the delayed failure data for 235 Ksi and 207 Ksi smooth strength level center-notched tensile specimens respectively. Although several of the specimens failed at significantly shorter times in the 235 Ksi strength material when exposed to the distilled water environment, no consistent effect of chloride concentration was present at either strength level. In 4340 steel, the strength level had a large effect on the stress corrosion process as evidenced by the order of magnitude difference in failure times between the 235 Ksi and 207 Ksi strength materials. The range of stress over which environmentally-induced delayed failure occurred was comparable for both materials, however the time to failure was approximately an order of magnitude greater for the lower strength level steel.

The stress corrosion cracking susceptibility of the 4340 steel under effectively plane strain conditions was evaluated by testing 235 Ksi strength material as a cantilever beam (see Figure 10). A noticeable difference was apparent in the stress corrosion susceptibility of the steel in the distilled water and chloride environments. The distilled water produced failure of the beam specimens in times which were almost an order of magnitude less than those obtained in the 1.5N and 3.0N NaCl solutions.

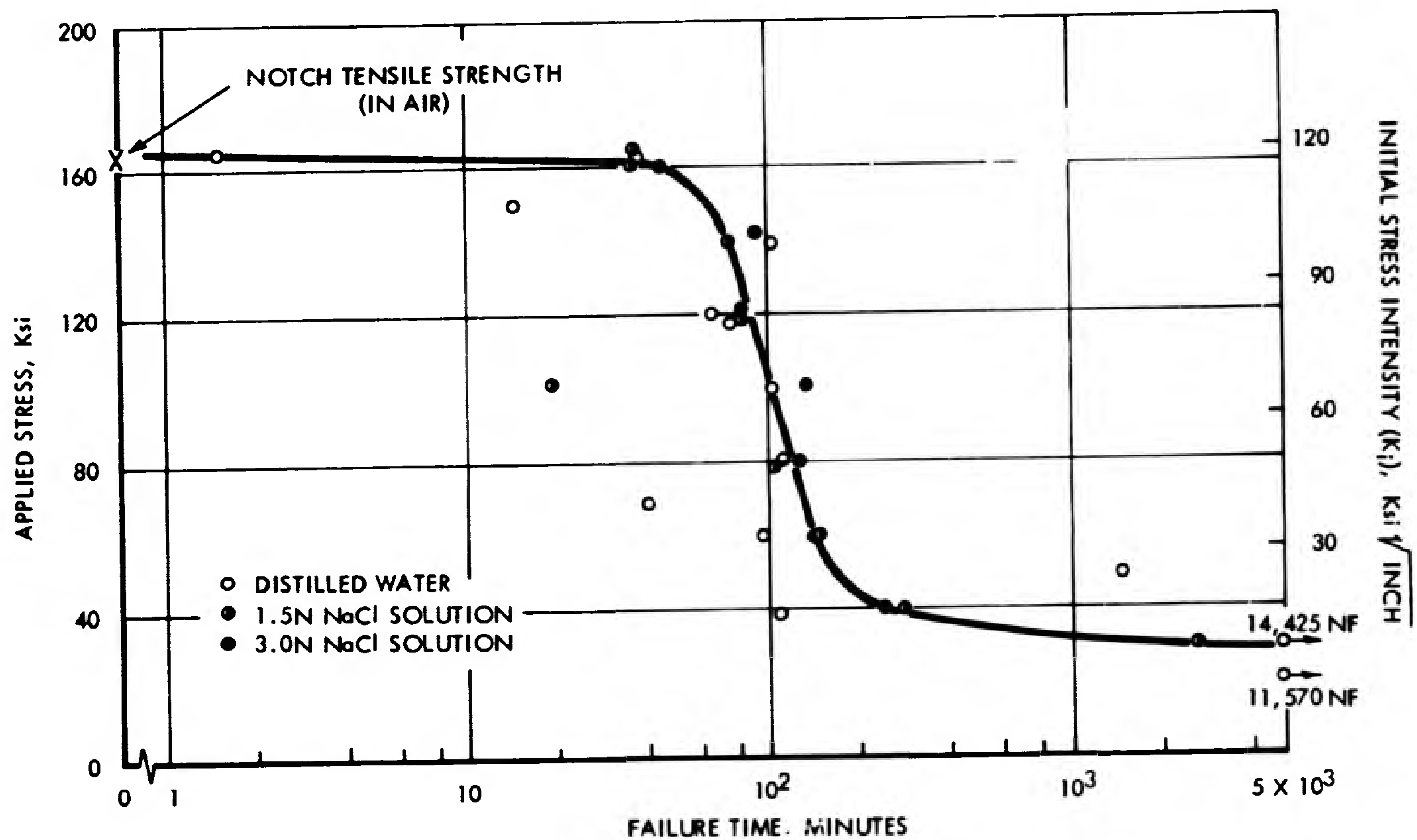


Figure 8. Delayed Failure of AISI 4340 Steel (235 Ksi Strength Level) Center-Notch Specimens.

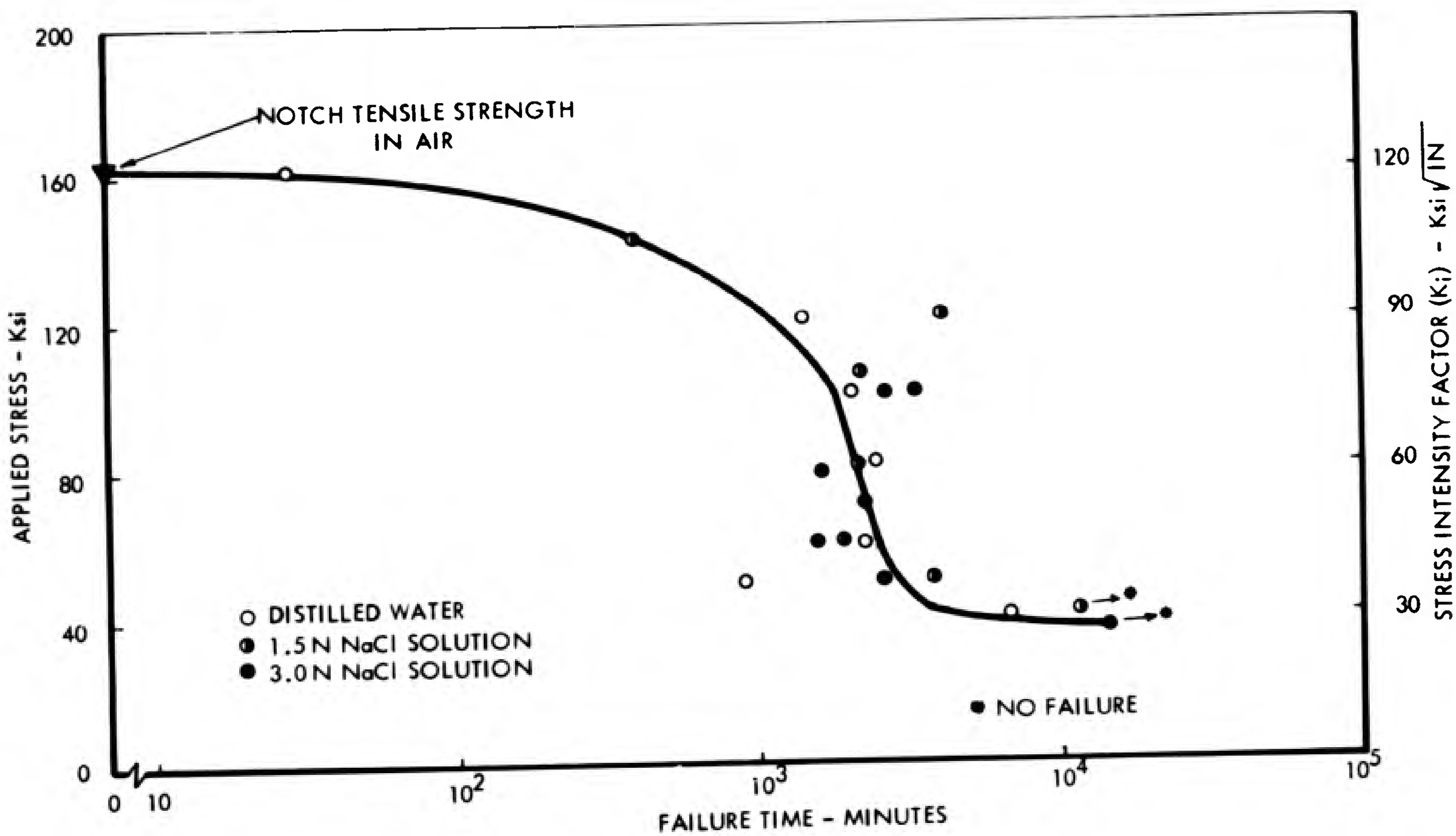


Figure 9. Delayed Failure of AISI 4340 Steel (207 Ksi Strength Level) Center-Notch Specimens.

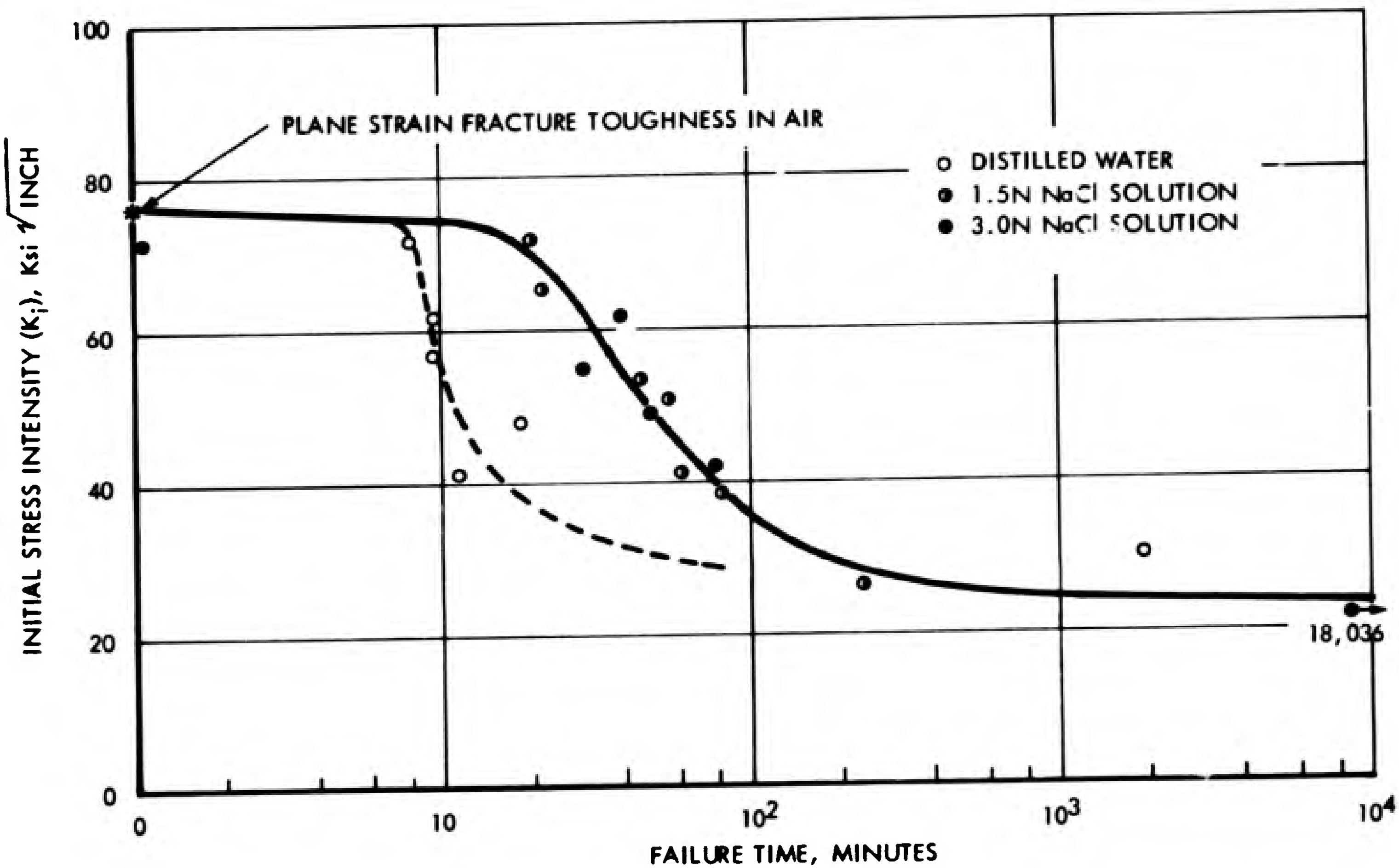


Figure 10. Delayed Failure of AISI 4340 Steel (235 Ksi Strength Level) Cantilever Loaded Notch Bend Specimens.

The concentration of chlorides above 1.5N apparently had little significance on the fracture characteristics and the data for the 1.5N and 3.0N solution exhibited identical failure behavior.

The retarding effect of chlorides in the aqueous environment observed in the cantilever beam tests on the 4340 steel also occurred in tests of smooth tensile specimens which were exposed to all three environments at stresses from 0.9 to 1.0 times the yield strength (see Table 3). Failures occurred in slightly more than 500 hours for only those 235 Ksi strength level specimens exposed to distilled water at stresses of 1.0 and 0.96 times the yield strength. In chloride solutions, more than 800 hours were accumulated with no failures. One specimen of 207 Ksi strength level material logged over 900 hours in distilled water at the yield stress with no failure. The smooth specimens which did not fail were unloaded and subjected to metallographic examination. Photomicrographs depicting representative environment-specimen interfaces in the 235 Ksi strength level steel exposed to distilled water and 3.0N NaCl are shown in Figure 11. A slightly more irregular interface and some intergranular cracking was produced by distilled water (Figure 11a). These data indicate that the chloride content retards the crack initiation phase of the stress corrosion process in 4340 steel.

The very large difference in failure times between the precracked and smooth sheet specimens indicates the significant contribution which the presence of a defect has on the overall failure process. An indication of the size of the defect produced in the smooth specimens is given in Figure 12 which shows the fracture surface of a specimen (235 Ksi strength level) that failed after 510 hours in a distilled water environment at an applied stress that was 0.96 of the yield strength.

The fracture surface of the 4340 specimens in both the sheet and bend specimens consisted of three distinct regions; the fatigue precrack, the slow environmentally-induced crack growth, and the rapid terminal crack propagation. An illustration of the failure mode in 4340 bend specimens, broken in air and in a distilled water environment, is presented in Figure 13. The stress corroded region has a surface which is considerably rougher than the fast fracture area. The center-notch specimens showed a comparable fracture morphology with the exception that the fast fracture occurred predominantely by a slant mode. In the case of the stress corrosion phase of the crack extension, the irregular surface could be directly related to the tendency of the main crack to branch during the propogation sequence.

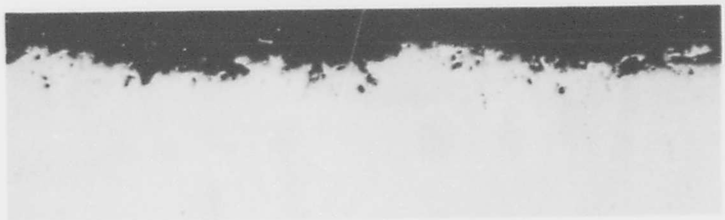
B. <u>Influence of Specimen Geometry</u> -- Comparisons of the delayed failure characteristics of the 4340 steel as a function of the specimen type are presented in Figure 14 for the three environments. The results indicate that at a specific value of the applied stress intensity parameter (K_i), the cantilever beam specimens produced failures in significantly shorter times than the center-notched sheet specimens. The critical stress intensity parameter, designated as K_{ISCC} (8), below which delayed failure was not observed was comparable in both specimen types. On this basis, stress corrosion data obtained on precracked sheet specimens can be used along with the appropriate fracture mechanics analysis to define the lower limit of environmentally-induced failure in other specimen types. The results also suggest that the initiation of environmentally-induced crack growth is governed by plane strain conditions at the specimen midplane.

TABLE 3

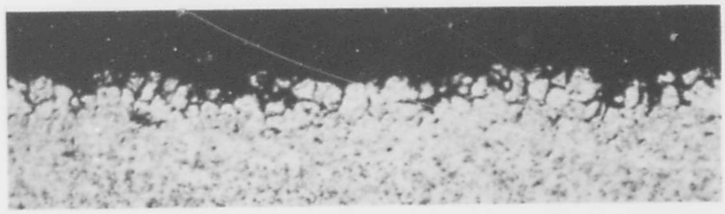
SUMMARY OF DELAYED FAILURE TESTS
ON
AISI 4340 STEEL SMOOTH SPECIMENS

Material Condition	Environment	Applied Stress-to-Yield Strength Ratio	Failure Time
500°F Temper	Dist. Water	1.0	523
500°F Temper	Dist. Water	0.963	510
500°F Temper	Dist. Water	0.950	210 NF*
500°F Temper	1.5N NaCl Aqueous Solution	1.0	234 NF
500°F Temper	1.5N NaCl Aqueous Solution	0.975	234 NF
500°F Temper	1.5N NaCl Aqueous Solution	0.963	810 NF
500°F Temper	1.5N NaCl Aqueous Solution	0.90	880 NF
500°F Temper	3.0N NaCl Aqueous Solution	1.0	640 NF
500°F Temper	3.0N NaCl Aqueous Solution	0.963	809 NF
700°F Temper	Dist. Water	1.0	189 NF
700°F Temper	Dist. Water	1.0	916 NF
700°F Temper	Dist. Water	0.975	215 NF
700°F Temper	3.0N NaCl Aqueous Solution	0.975	881 NF

* NF - Indicates no failure



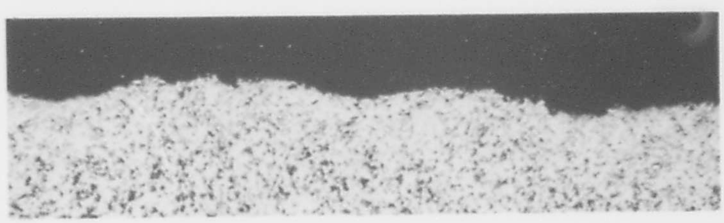
UNETCHED 250 X



2% NITAL ETCH 500 X

(a) DISTILLED WATER ENVIRONMENT, σ_A = 140.5 ksi

UNETCHED 250 X



2% NITAL ETCH 500 X

(b) 3.0 N NaCl ENVIRONMENT: σ_A = 200.6 ksi

Figure 11. Corrosion of AISI 4340 Steel (235 Ksi Strength Level) Under an Applied Stress and Exposed to a) distilled water, and b) 3.0 N NaCl Solution.

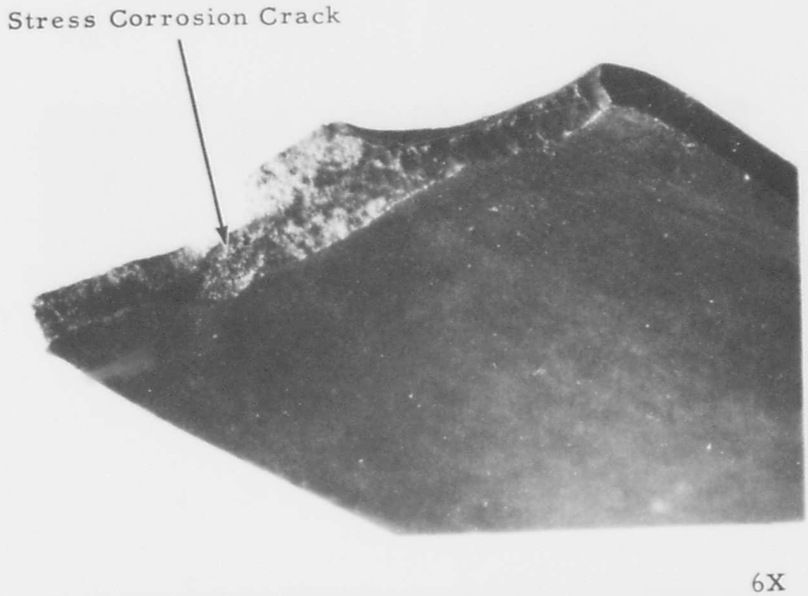
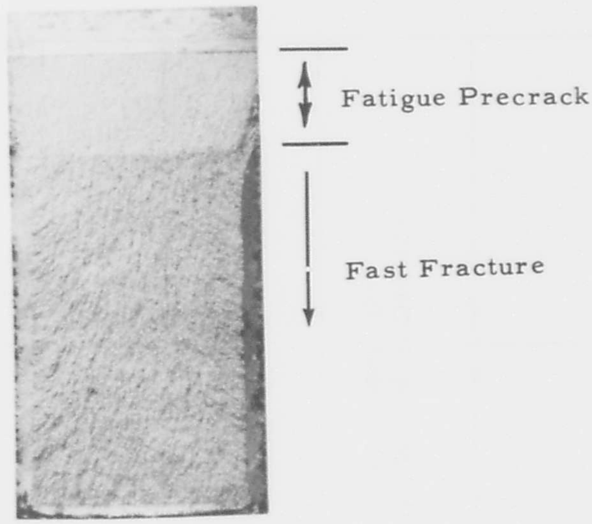
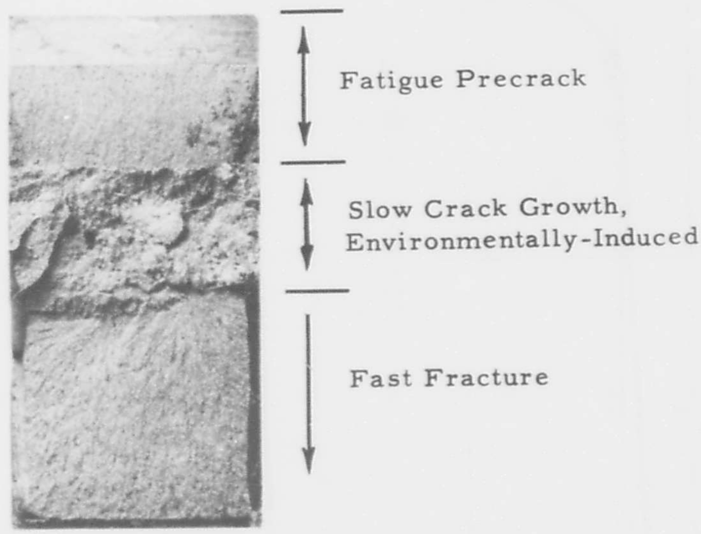


Figure 12. Fracture Appearance of 4340 (235 Ksi Strength Level) Smooth Specimen which Failed After 510 Hours at an Applied Stress of 0.96 of the Yield Strength, Distilled Water Environment, Room Temperature Test.



Air Environment
K_{IC} = 73.3 Ksi $\sqrt{in.}$



Distilled Water
Environment
K_i = 62.2 Ksi $\sqrt{in.}$

Figure 13. Fracture Appearance of 4340 Cantilever Beam Bend Specimens, (235 Ksi Strength Level).

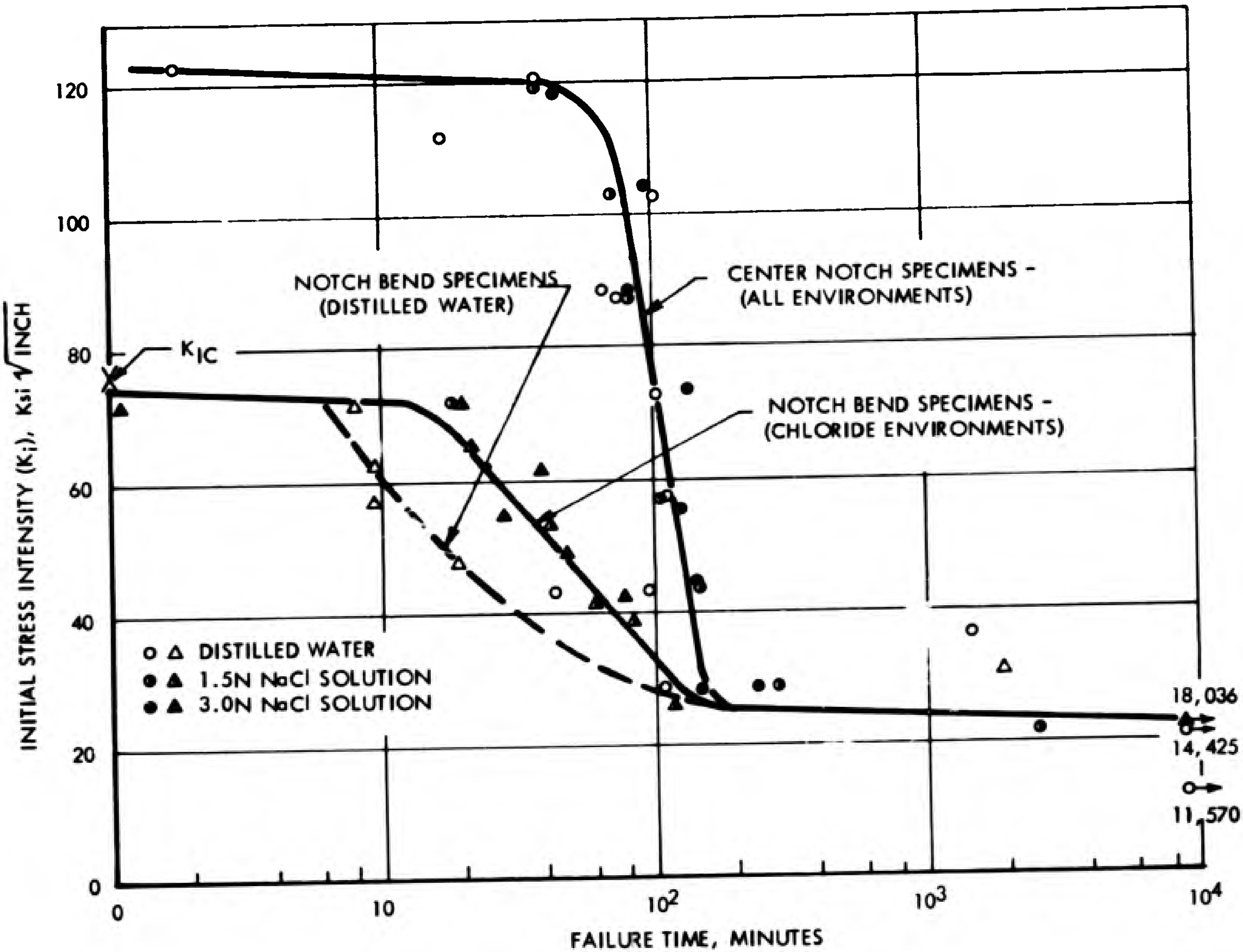


Figure 14. Delayed Failure of AISI 4340 Steel (235 Ksi Strength Level) as a Function of Applied Stress Intensity Parameter.

The critical stress value below which delayed failures are not observed should be dependent on the absolute value of the stress intensity parameter, thus producing a characteristic K_{ISCC} value. The time to failure, however, should be more directly related to the ratio of the applied stress intensity to the stress intensity at failure (K_i/K_c), since this parameter controls the total degree of slow crack growth that can be tolerated. A plot of the delayed failure characteristics of 4340 steel as a function of the K_i/K_c ratio is shown in Figure 15. With the exception of the failures of cantilever beam specimens in the distilled water environment, the failure times for both specimen types defined a reasonably consistent curve when plotted as a function of the K_i/K_{IC} ratio. At present no explanation is available for the difference in behavior between the center-notched and cantilever beam specimens exposed to the distilled water environment.

2. Delayed Failure of HP 9-4-45 Steel

A. Influence of Environment - Distilled water, 1.5N and 3.0N NaCl aqueous environments were applied at room ambient temperature to fatigue precracked center-notch tensile specimens at constant load. Delayed failures were realized in all environments and the data are summarized in Figure 16. With a few exceptions, the distilled water and NaCl solution test data formed separate curves below 150 Ksi.

Failures were produced in less than a minute at stresses greater than 92% of the notch tensile strength, which is about 60,000 psi below the yield strength for 9-4 steel at the 650° temper condition used in this study. Below 89% of the notch tensile strength, environmentally-induced failure did not occur in most cases until at least 750 minutes.

Delayed failure curves for 9Ni-4Co steel under plane strain conditions (cantilever beam notch bend tests) are presented in Figure 17. The plane strain data show much wider scatter than did the plane stress data (center-notch tests). However, the same general feature - failures occurring after about 700 minutes below 90% of the K_{IC} - was observed.

In general, the higher chloride content solutions were more aggressive toward HP 9-4 steel than distilled water. This trend was quite definite in the center-notched sheet specimens but, because of the data scatter, was not as well defined for the notch bend tests.

The tendency for scatter to occur in the notch bend specimens of the HP 9-4 steel could be directly related to the unique crack morphology present in this material. Slow crack growth seemed to emanate from a point source (or sources) along the precrack front. Examples of this failure characteristic are shown in Figures 18 and 19. The specimen in Figure 19 is particularly effective in showing a stress corrosion crack which initiated at a point along the front of the precrack and propagated beneath the precrack until the specimen could no longer sustain the load. The fact that the stress corrosion cracks in HP 9-4 steel did not propagate uniformly, plus the observation that the failure process seemed to be strongly dependent on isolated events at the crack tip, explain the increased scatter in the HP 9-4 steel data.

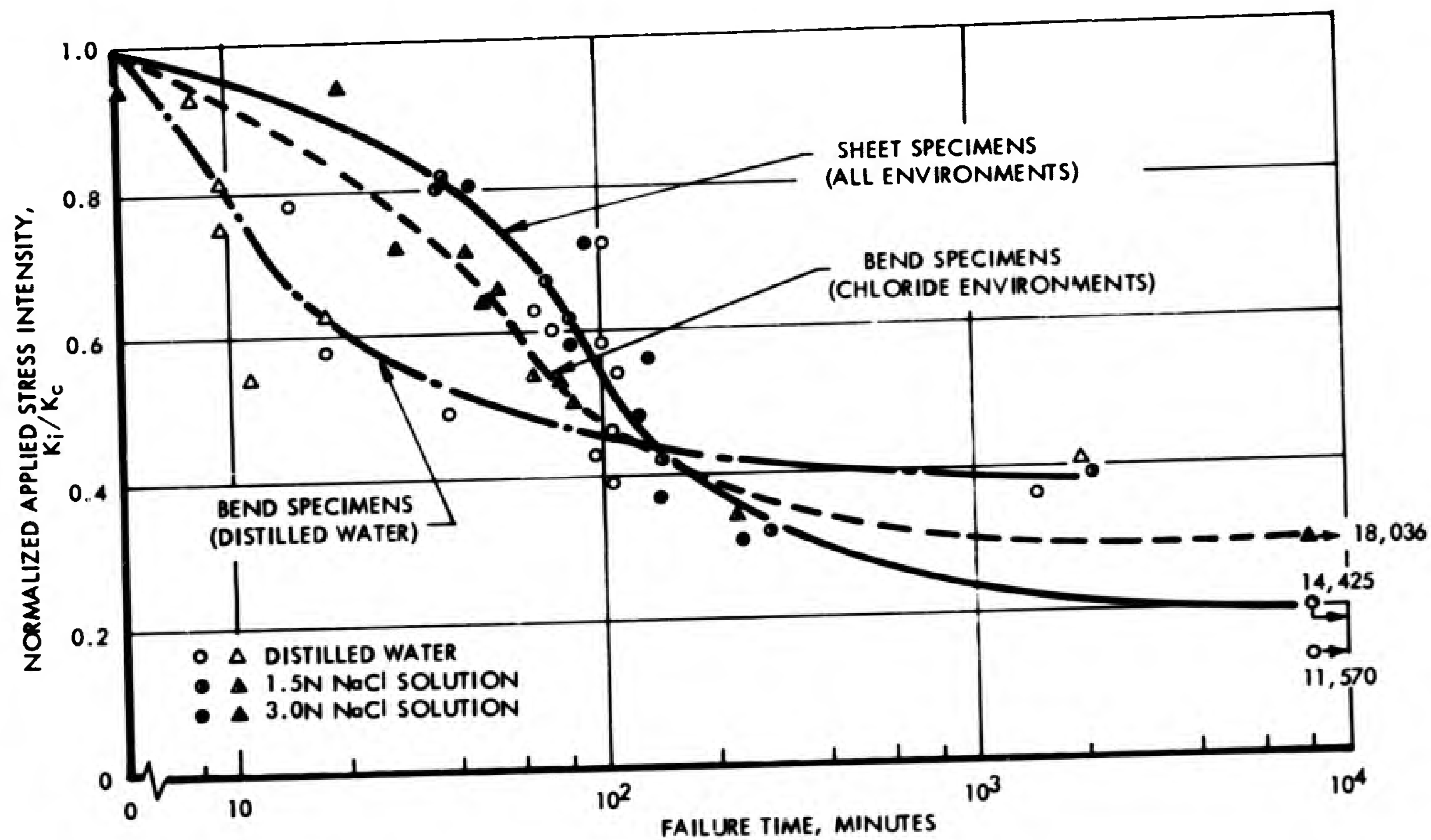


Figure 15. Composite Representation of Delayed Failure in 4340 Steel (235 Ksi Strength Level.)

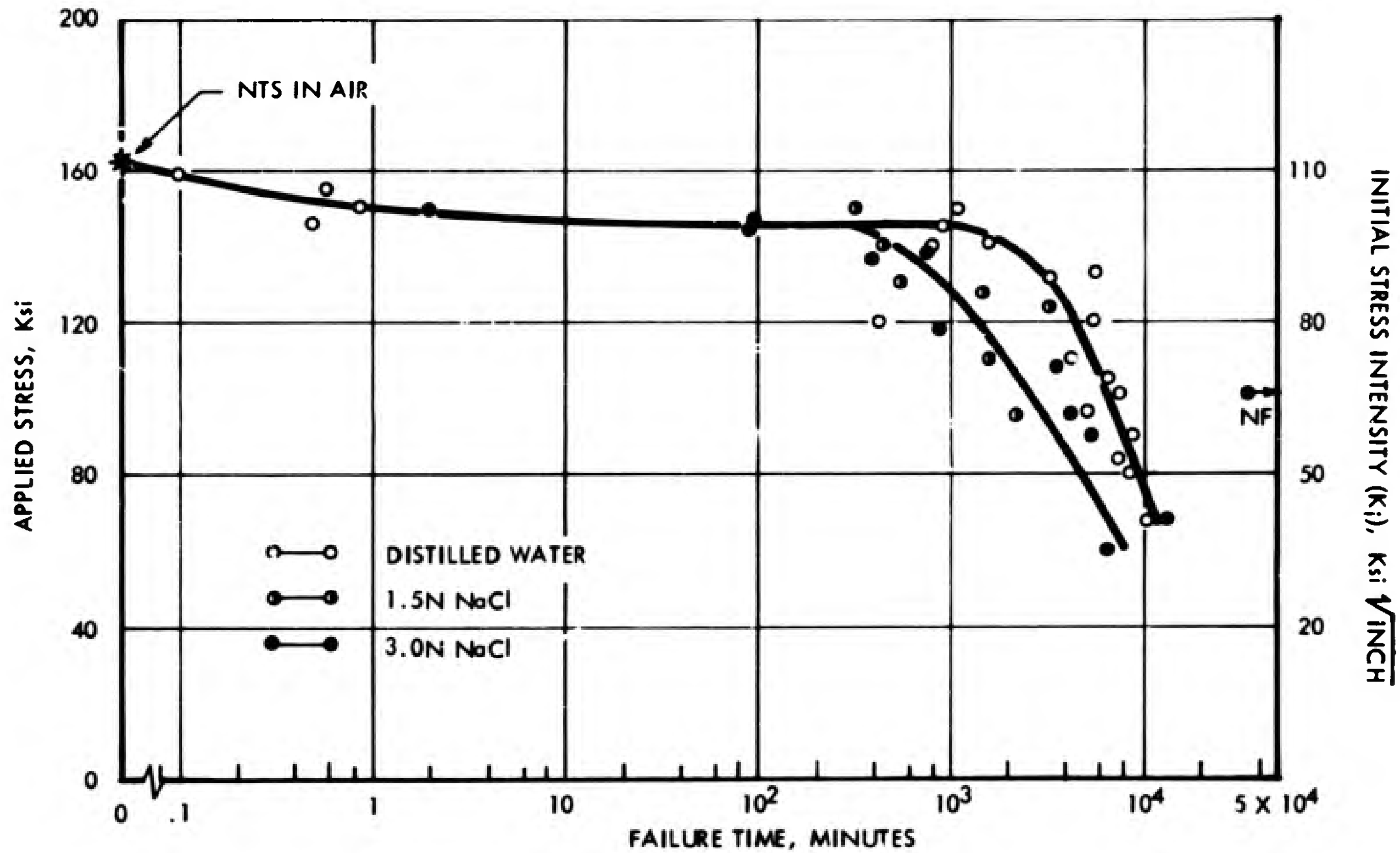


Figure 16. Delayed Failure of HP 9-4-45 Steel (242 Ksi Strength Level) Center-Notch Specimens.

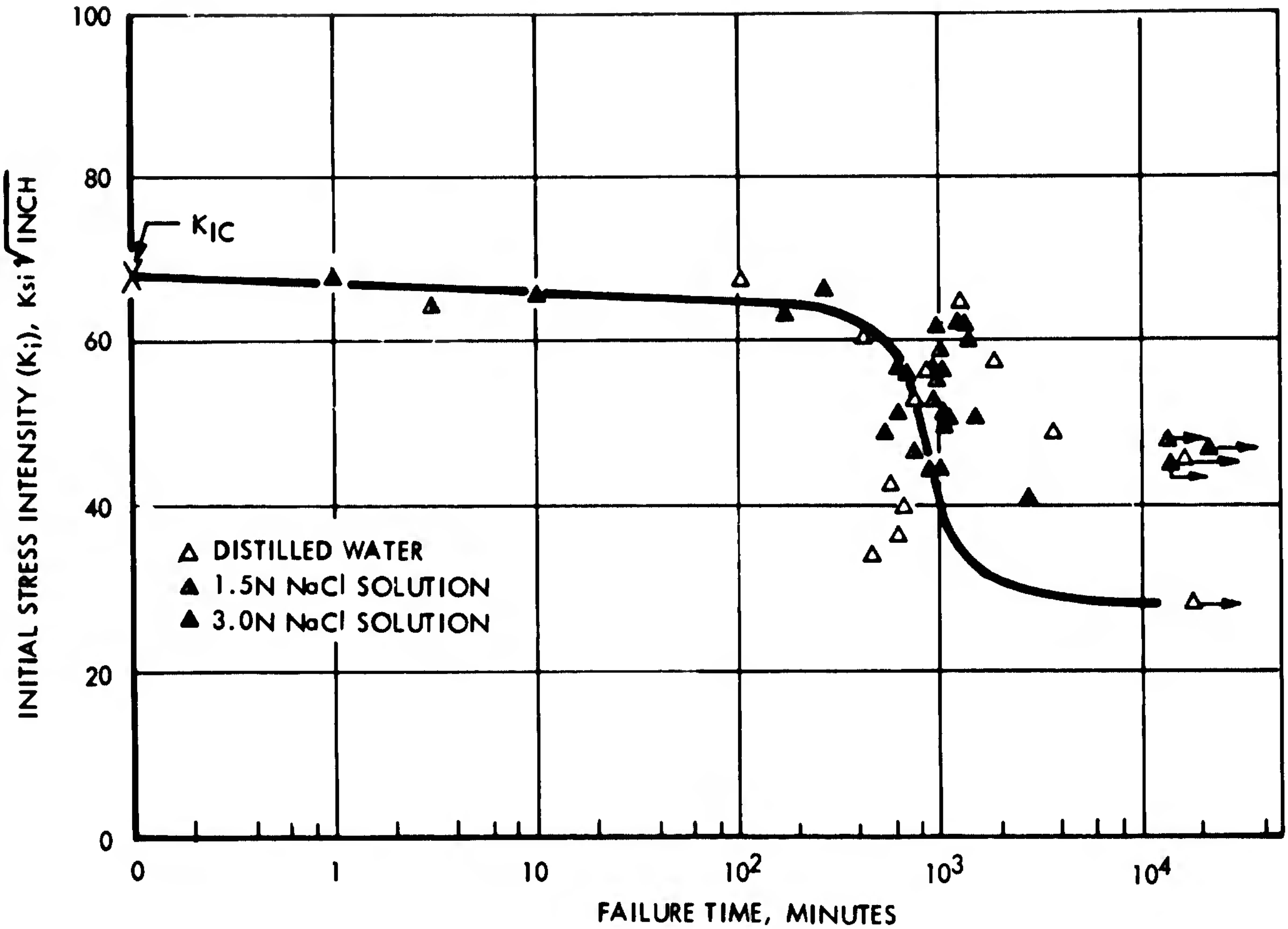
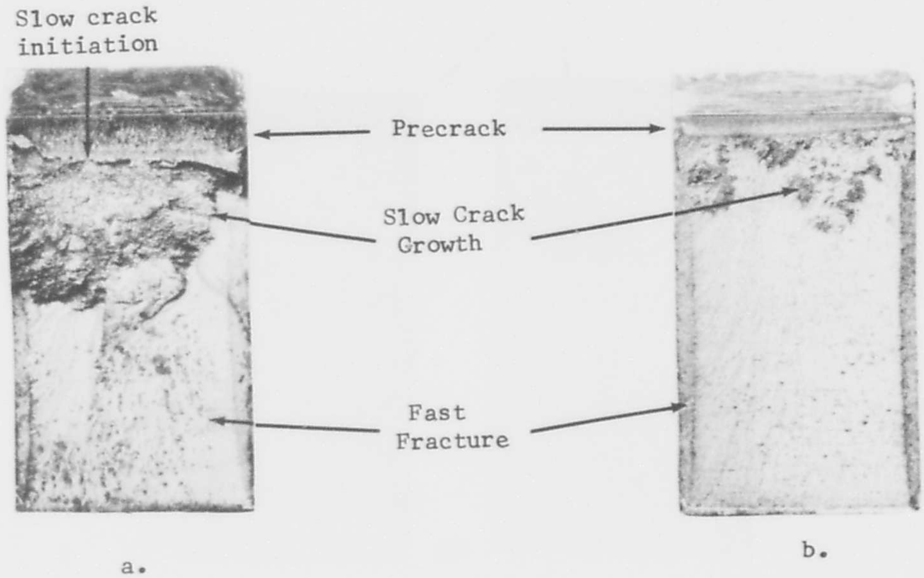


Figure 17. Delayed Failure of HP 9-4-45 Steel (242 Ksi Strength Level) Cantilever Loaded Notch Bend Specimens.



a. Ki - 49.0 Ksi $\sqrt{in}$, failure time - 3822 minutes, distilled water environment.

b. Ki - 50.5 Ksi $\sqrt{in}$, failure time - 1620 minutes, 3.0 N NaCl environment.

'igure 18. Examples of Fracture Surfaces of HP 9-4-45 Steel, Notch Bend Specimens.

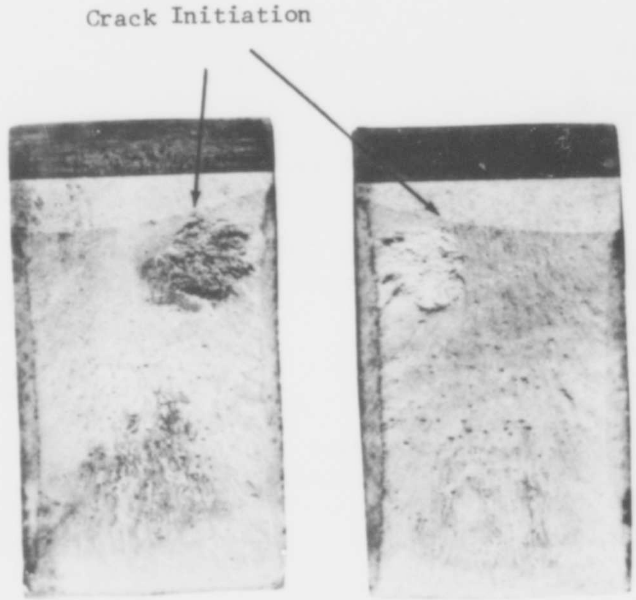


Figure 19. Fracture Surface of HP 9-4-45 Steel Notch Bend Specimens; K_i - 51.6 Ksi $\sqrt{\text{inch}}$, t_f - 636 minutes, 3.0 N NaCl Environments.

Smooth tensile specimens of HP 9-4-45 steel were exposed to all three environments at stresses in the range of 1.00 to 1.05 times the yield strength. Failures occurred at about 660 hours in distilled water, at about 600 hours in 1.5N NaCl and at about 500 hours in 3.0N NaCl (see Table 4) for specimens stressed above the 0.2% offset yield strength. This indicates an agreement with the pre-cracked data that the chloride solutions are more corrosive than distilled water, and that the higher the chloride content, the more agressive the solution (as far as the pitting and crack initiation phases of stress corrosion cracking in 9NI-4CO steel are concerned). In this respect the behavior of the HP 9-4 steel differed from the 4340 steel where the distilled water environment was more degrading.

B. Influence of Specimen Geometry - The delayed failure curves are presented as a function of the applied stress intensity parameter K_i in Figures 20, 21 and 22. The K_{ISCC} parameter is not defined for the center-notched specimens and in the case of the notch bend tests, a rather wide scatter band between 30.0 and 40.0 Ksi $\sqrt{in.}$ occurred. The similarity between the failure times produced in the center-notched sheet and notched bend specimens when presented as the K_i/K_c ratio is shown in Figure 23 for each of the environments evaluated. Although a considerable scatter exists, the conclusion obtained from the 4340 steel data that the K_i/K_c ratio defines failure times which are relatively insensitive to specimen geometry, also applies for the HP 9-4 steel.

A comparison of the delayed failure characteristics of the HP 9-4 and 4340 steels based on the K_i/K_c ratio is shown in Figure 24. At a given value of this ratio, the time to produce failure in the HP 9-4 steel with a higher alloy content, yet approximately the same fracture toughness, is almost two orders of magnitude greater than in the 4340 steel heat treated to a comparable strength level. The results tend to indicate, however, that the ratio below which failure does not occur may be comparable for both materials. Crack growth curves to be presented in the next section will show that the extended failure time which occurs in the HP 9-4 material is a result of both an increased incubation time preceding crack growth and a slower crack growth rate.

3. Crack Growth Behavior

Slow crack propagation characteristics in 4340 steel center-notch specimens were measured using resistance techniques. Discontinuous crack growth was observed in all instances and an incubation time was often required before slow crack growth initiated. The influence of environment (0 and 1.5N NaCl solutions) on the crack growth characteristics of the 235 ksi strength level 4340 is shown in Figure 25 for a constant applied stress. No significant variation in crack growth characteristics was observed.

A comparison of the crack growth kinetics for the two strength levels of 4340 steel is given in Figure 26. At an applied stress level of approximately 100 Ksi, neither material showed a distinct incubation time, however the steel at the 207 Ksi strength level exhibited a much lower crack growth rate and distinct discontinuous periods where the cracking temporarily stopped for several minutes. The crack growth rate studies indicate that the increased failure time present in the 207 Ksi steel could not be accounted for solely by the fact that the crack had to grow a larger distance prior to rapid fracture. The differences in strength level had a very definite influence on the rate of stress corrosion cracking, as well as the critical crack size. An example of the crack growth curve obtained

TABLE 4

SUMMARY OF DELAYED FAILURE TESTS ON HP 9-4-45 STEEL SMOOTH TENSILE SPECIMENS

Applied Stress	Environment	Failure Time (Hours)	σ_a/σ_{ys}
222.9	H_2O	505 NF*	1.00
230.0	H_2O	661	1.03
222.9	1.5N NaCl Aqueous Solution	505 NF	1.00
234.0	1.5N NaCl Aqueous Solution	604	1.05
222.9	3.0N NaCl Aqueous Solution	774 NF	1.00
230.0	3.0N NaCl Aqueous Solution	502	1.03

* NF - Indicates no failure

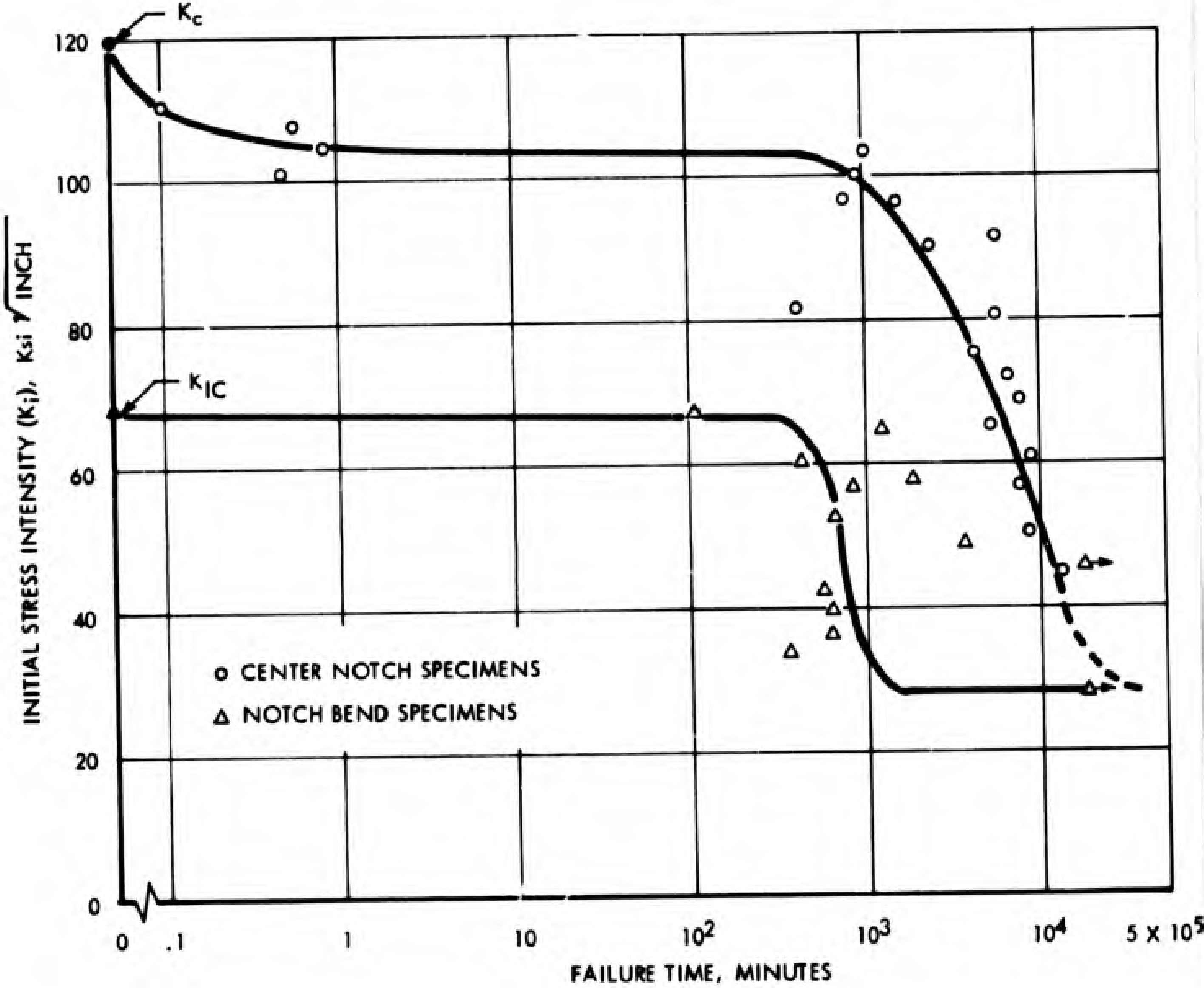


Figure 20. Delayed Failure of HP 9-4-45 Steel as a Function of Applied Stress Intensity - Distilled Water Environment.

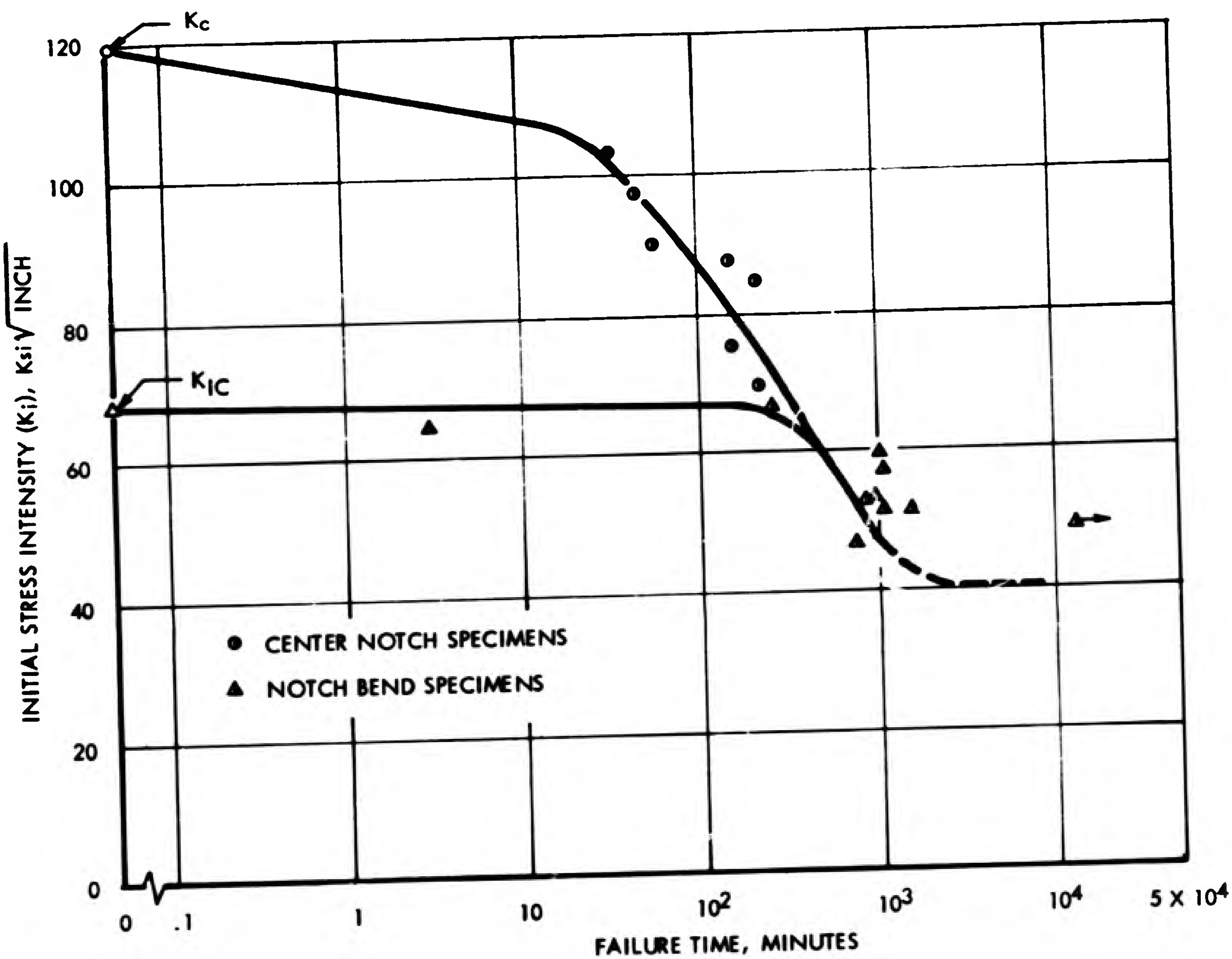


Figure 21. Delayed Failure of HP 9-4-45 Steel as a Function of Applied Stress Intensity - 1.5 N NaCl Aqueous Environment.

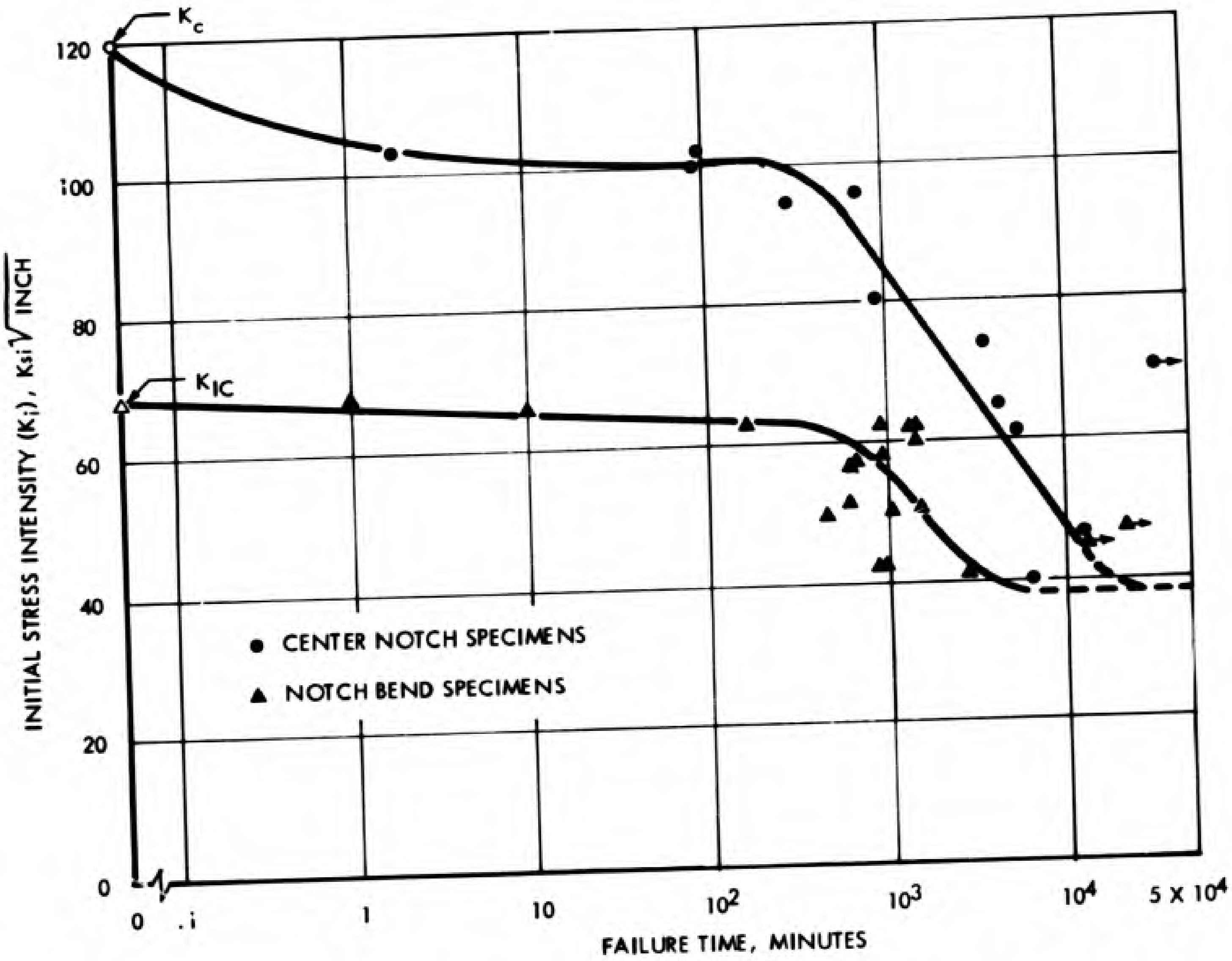


Figure 22. Delayed Failure of HP 9-4-45 Steel as a Function of Applied Stress Intensity - 3.0 N NaCl Aqueous Environment.

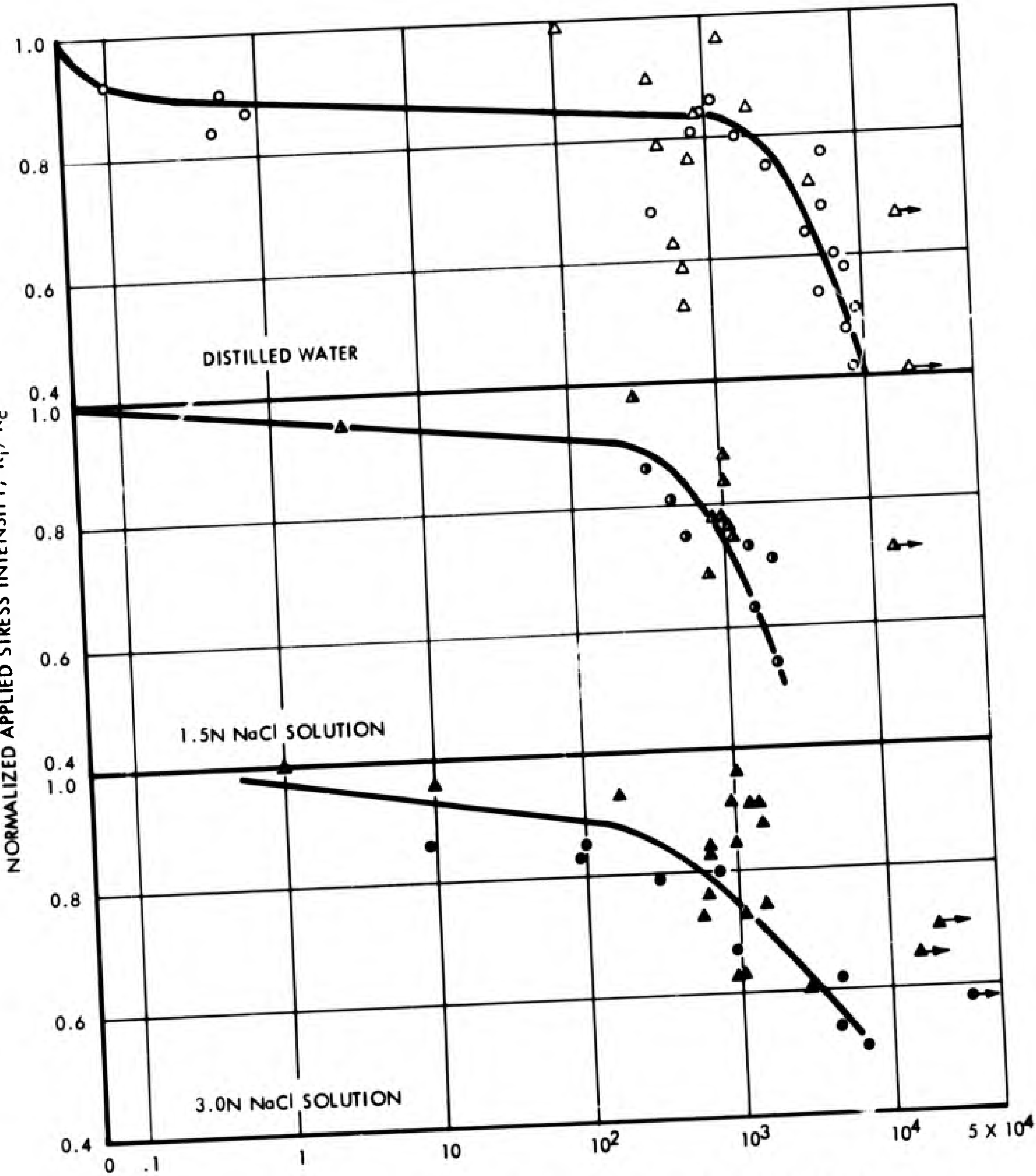


Figure 23. Delayed Failure Curves for HP 9-4-45 Steel (242 Ksi Strength Level) using Normalized Applied Stress Intensity.

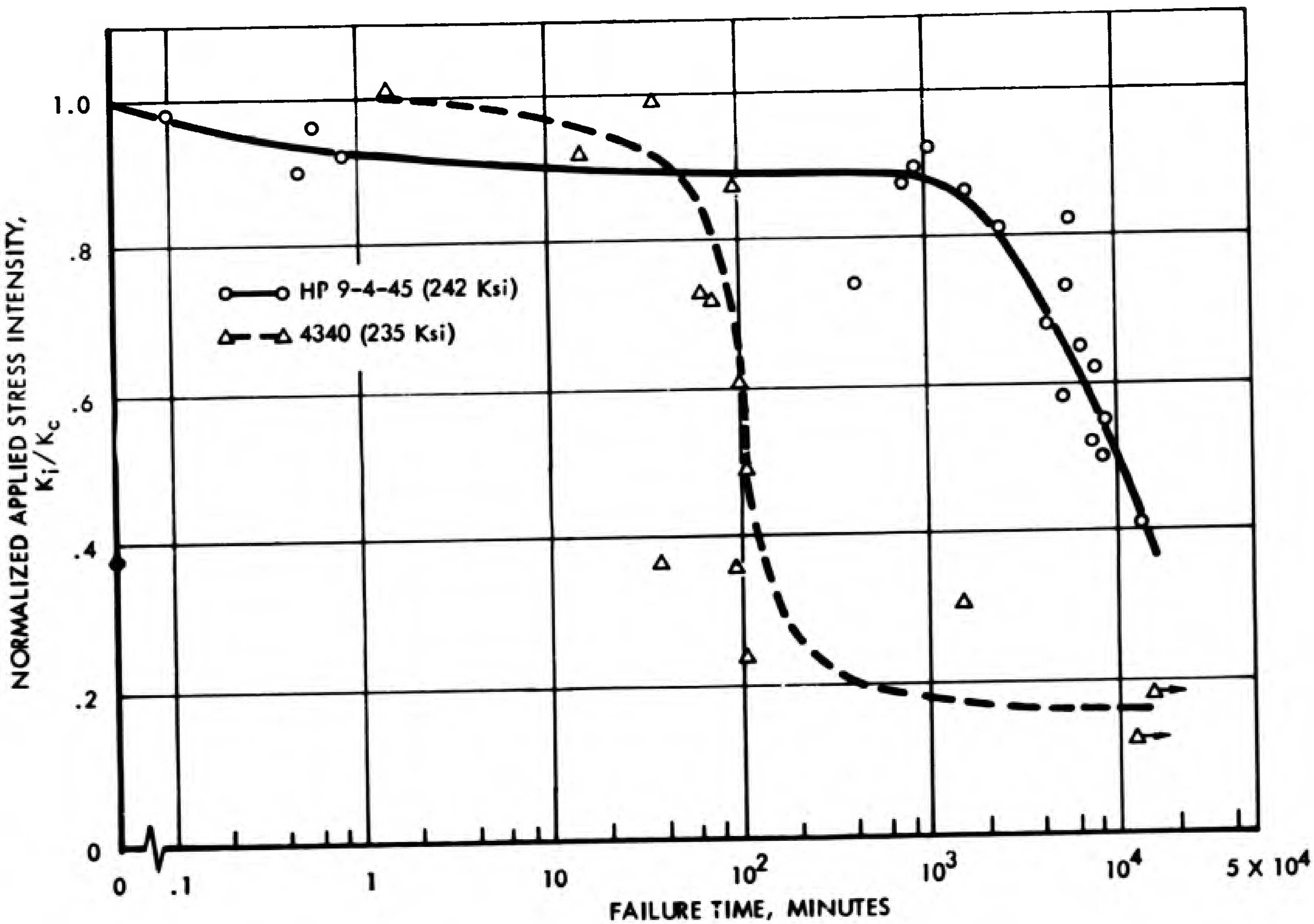


Figure 24. Comparison of Delayed Failure Curves of AISI 4340 Steel and HP 9-4-45 Steel in Distilled Water Environment using a Normalized Applied Stress Intensity Function.

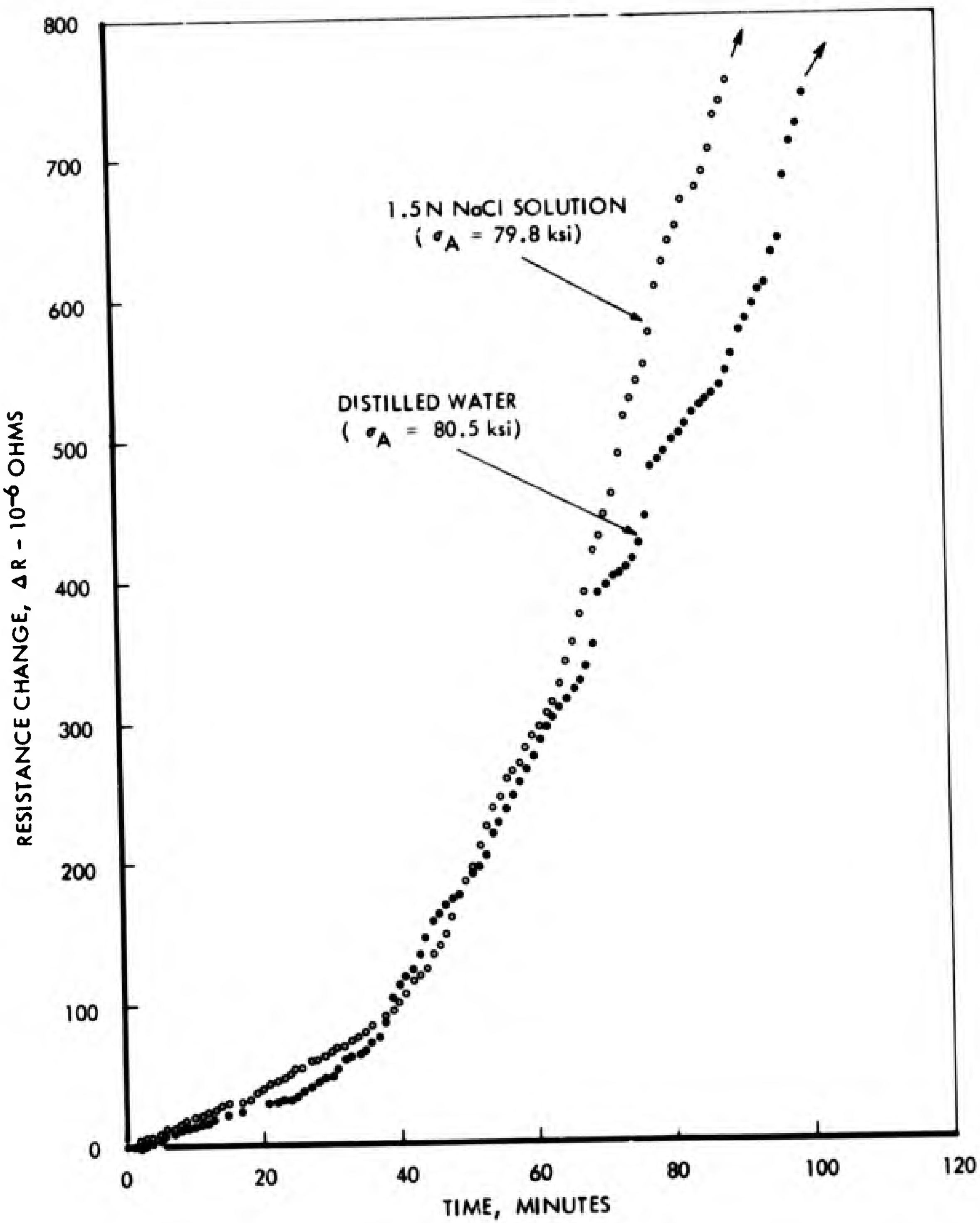


Figure 25. Slow Crack Growth C aracteristics of AISI 4340 Steel (235 Ksi Strength Level) Center-Notch Tensile Specimens in both Distilled Water and 1.5 N NaCl Solution.

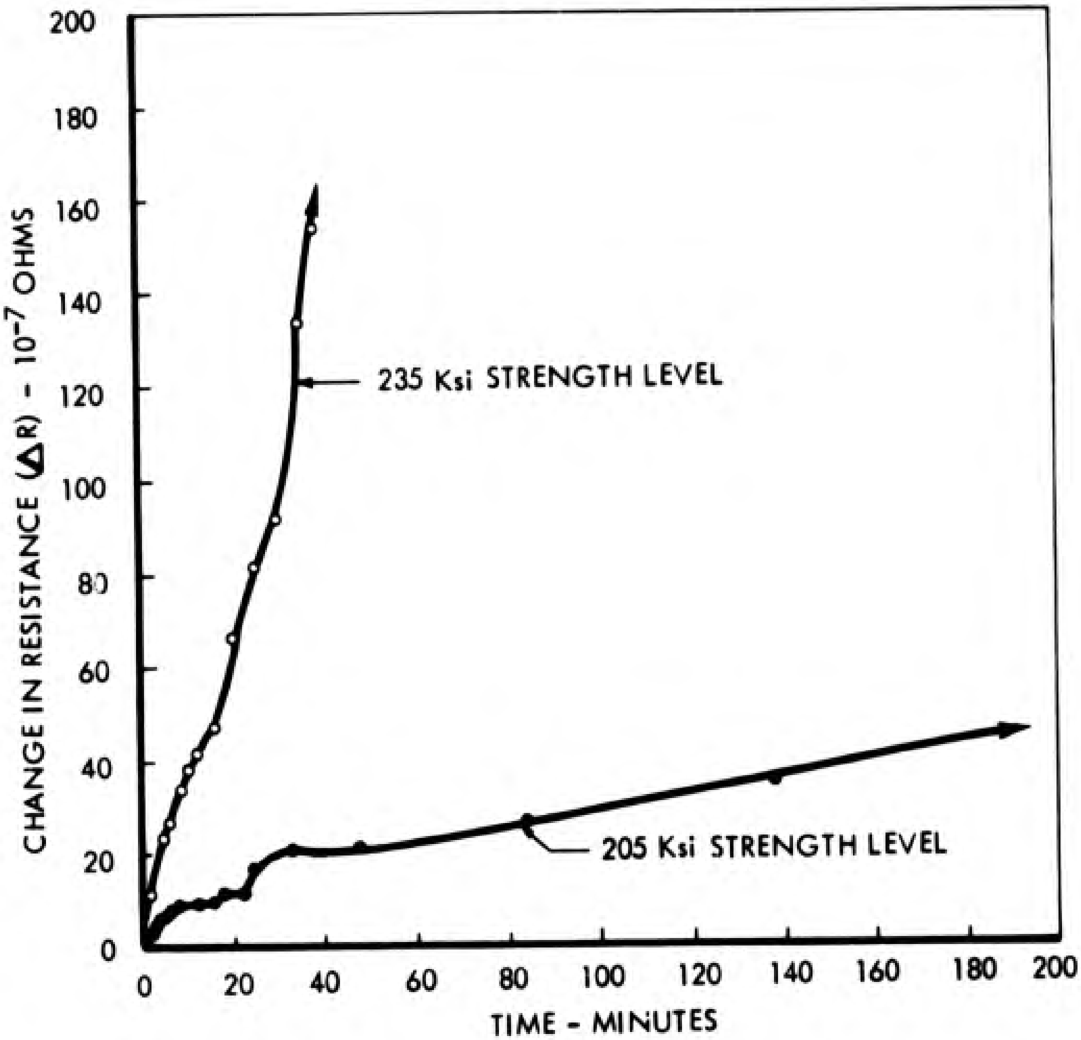


Figure 26. Variation of Crack Growth Behavior for 4340 Steel as a Function of Strength Level, 160 Ksi Applied Stress, Aqueous Environment.

from compliance measurements on HP 9-4-45 steel is shown in Figure 27. When compared to the 4340, the HP 9-4-45 steel exposed to the aqueous environments exhibited a relatively long incubation period prior to the initiation of slow crack growth. The crack growth was also characterized by discontinuous crack extension where appreciable time periods existed with no crack extension, followed by a rapid burst of crack growth.

In the precracked sheet specimens tested at lower values of applied stress, the delayed failure sequence consisted first of an incubation period where no crack extension was produced. This period was then followed by a macroscopically slow growth which led to total specimen failure. At the higher values of applied stress, no incubation period preceding crack extension was observed. In order to gain additional insight into the factors that were controlling the crack growth, tests were conducted on 4340 sheet with particular emphasis on the reversibility of the incubation time.

In these tests, specimens were exposed to a water environment and load for a time sufficient to allow some crack growth. The load and water were then removed and the specimen was aged at room temperature. Under these conditions (shown in Figure 28) there was some recovery of the incubation time. The test sequence was then varied to include aging in the water environment without load and aging under load without the water environment. When the water was present without a load, no recovery in the incubation time occurred during subsequent testing. When the load was present during aging, without the environment, the subsequent incubation time was considerably extended (see Figure 29).

The results of the aging studies suggest that the incubation period represents the time required for the environment to permeate (or dissolve) a film which is formed at the crack tip between the precracking and testing operations. At high values of applied stress the film cracks, the environment is in immediate contact with the metal, and no incubation time is observed. At lower values of applied stress, the film is only partially cracked and a certain incubation time is required for the environment to contact the crack tip. When the load and environment are removed, the film reforms and on subsequent testing, a secondary incubation time is observed. In the case where the aging is performed under the load without the environment, the film which forms is not ruptured by a subsequent load application and the environment must then permeate through the complete film which produces an increase in the incubation time.

The model indicates that the incubation time and the total failure time can be significantly extended by aging under load prior to the application of the environment; however, the crack growth period should not be influenced. The results of a test conducted under these conditions are shown in Figure 30. Aging under load prior to the application of the environment extended the incubation period by over an order of magnitude. The total failure time was also extended by this amount; however, the crack growth period was not influenced. The data indicate that the incubation period is caused by film formation which protects the metal from the environment. This film, once destroyed or permeated by the environment, does not reform during the stress corrosion process and apparently has little influence on the subsequent crack growth mechanism.

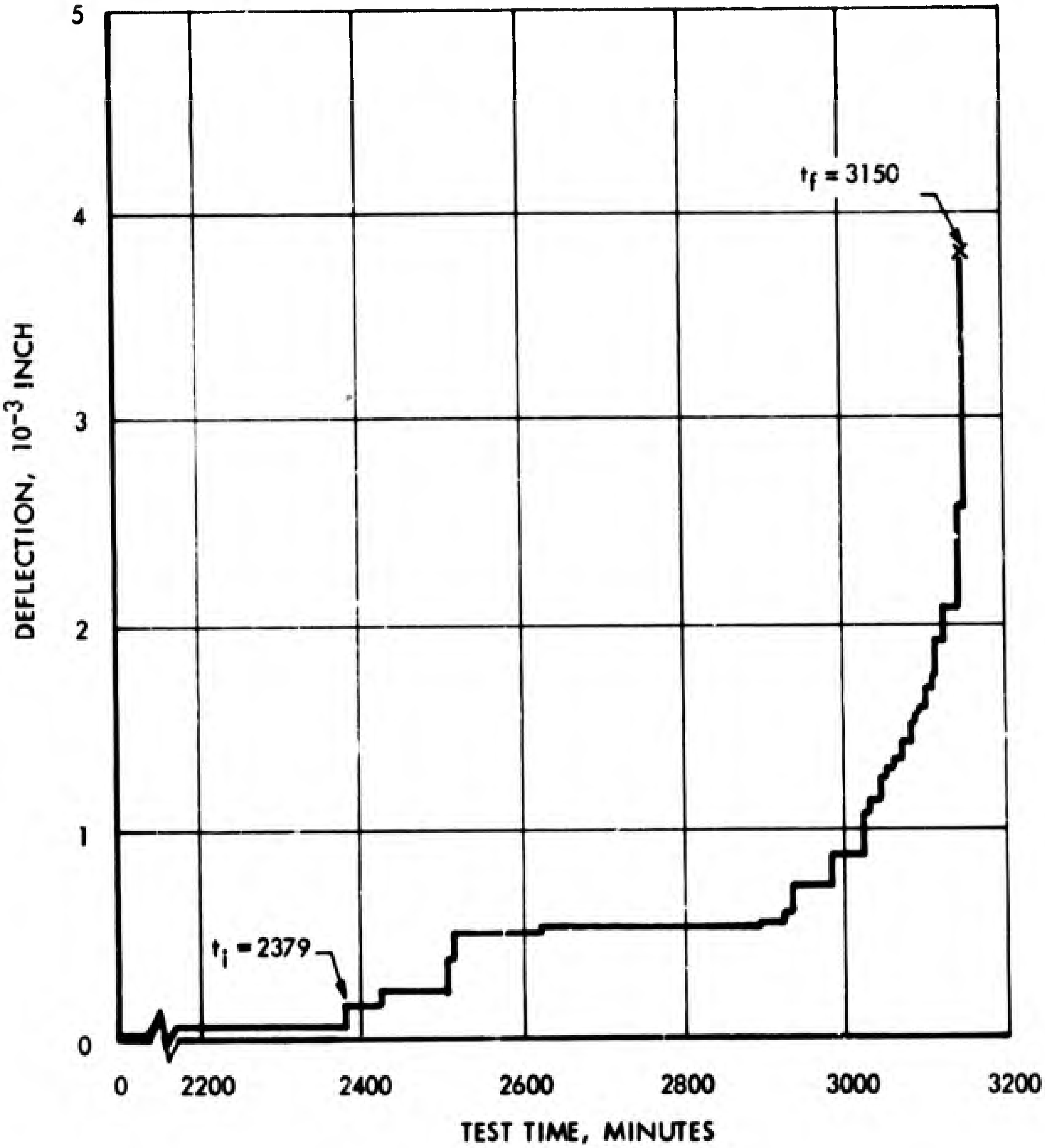


Figure 27. Example of a Crack Growth Curve Obtained from Compliance Measurements on HP 9-4-45 Steel in Distilled Water at 120 Ksi Applied Stress.

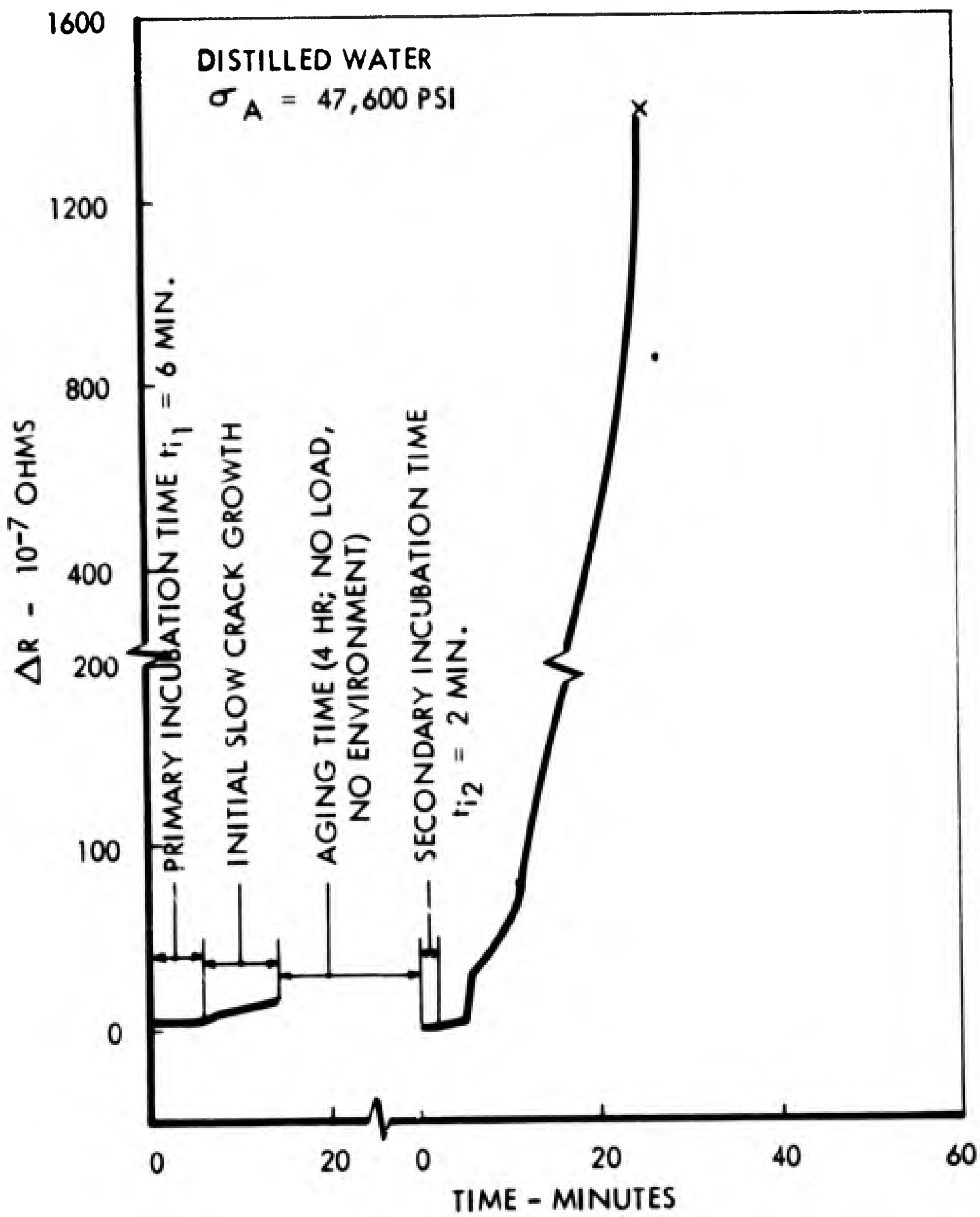


Figure 28. Recovery of Incubation Time during Aging; 4340 Steel, (235 Ksi Strength Level.)

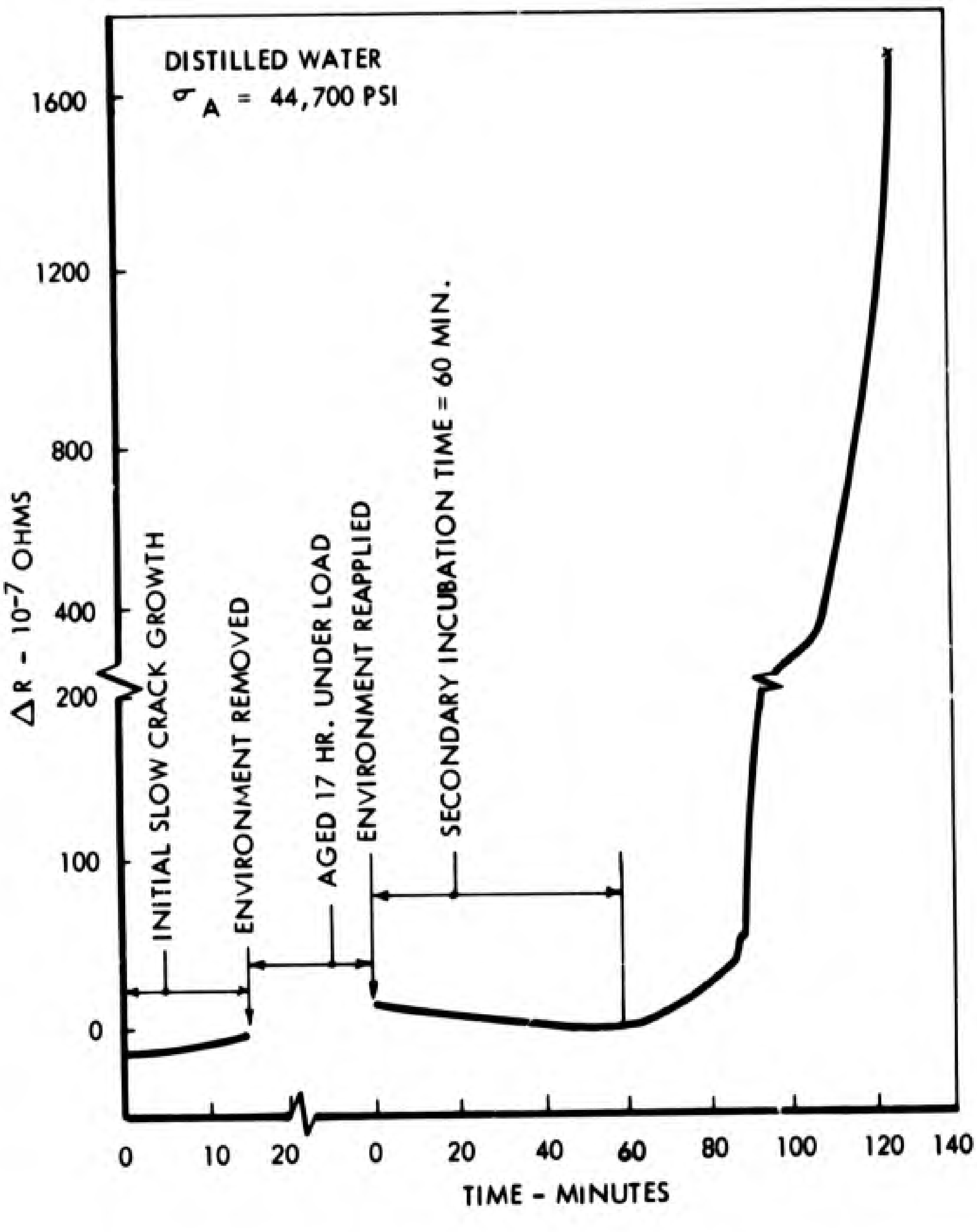


Figure 29. Increase in Incubation Time Produced by Aging Under Load; 4340 Steel (235 Ksi Strength Level.)

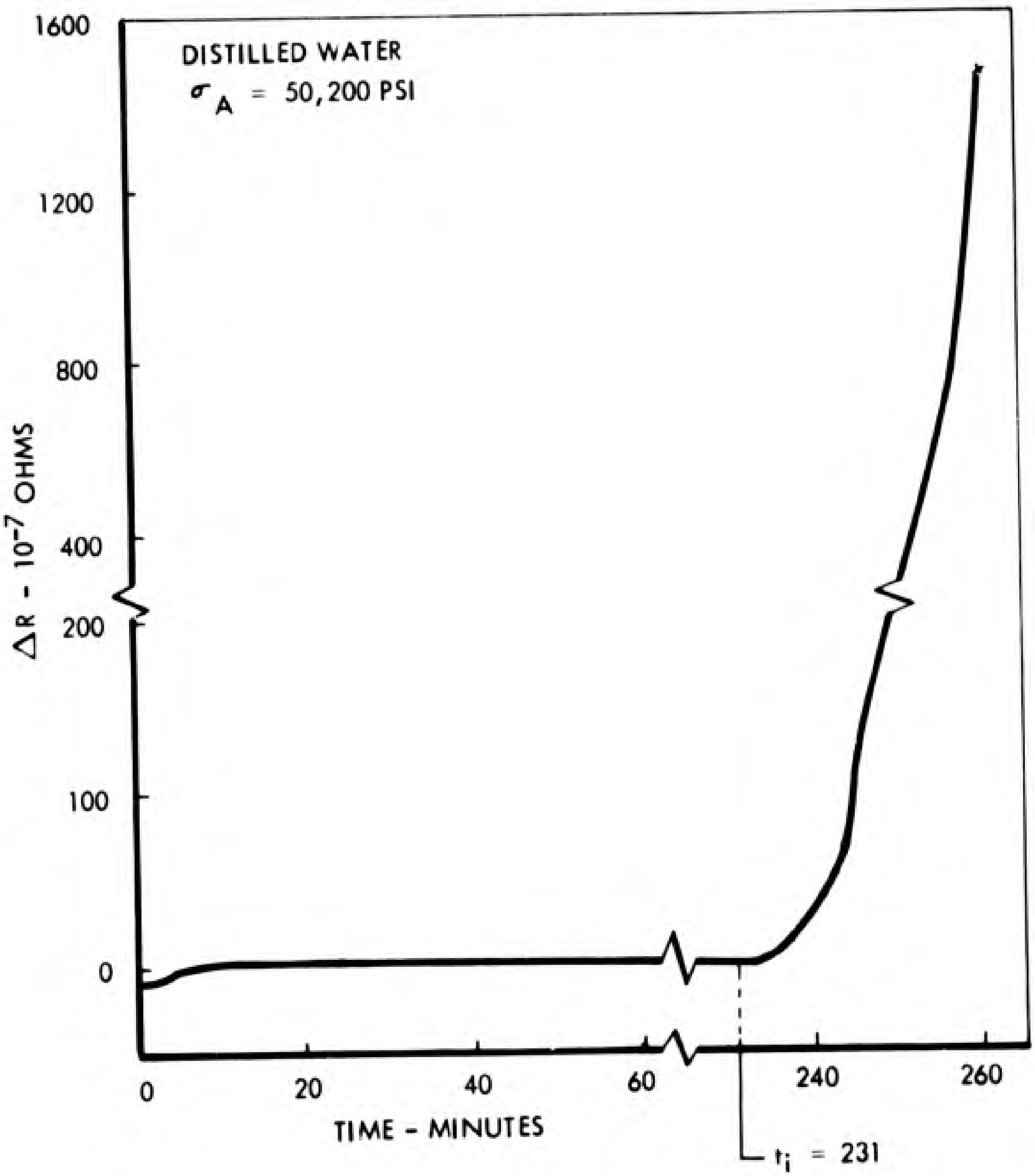


Figure 30. Extended Incubation Time Produced by Aging Specimen Under Load Prior to Application of an Environment; 4340 Steel (235 Ksi Strength Level.)

Crack growth measurements were made on the notch bend specimens to determine incubation times for slow crack growth. A typical curve is illustrated in Figure 31. The incubation times exhibited considerable scatter, so no definite relationship between incubation time and applied stress was apparent. For most tests, the incubation times were short (less than 10 minutes) and therefore contributed little to the observed failure times. These results are consistent with the concept developed from crack growth studies in center-notch specimens which involved film formation at the crack tip between the precracking and testing operations. If this film becomes very thick or is not ruptured upon application of the load, the incubation time (and failure time) can be extended as a result of the time required for the environment to permeate the film and initiate the stress corrosion process.

The extended incubation time present in the HP 9-4-45 steel studies suggests that the film formed in the higher alloy material is more impervious to penetration by the environment. The presence of such a film could aid in explanation of the unique fracture propagation mode observed in the 9-4 steels. If the film were penetrated at a point on the fatigue crack front, the subsequent crack propagation would be expected to be relatively rapid at that point while the remainder of the crack would not extend due to the protective nature of the film. The presence of a more protective film and its contribution to an extended incubation time does not represent a complete description of the improved resistance of the HP 9-4-45 steel to environmentally-induced failure. Once crack initiation occurs, for example in the center-notch specimen shown in Figure 27, the crack growth rate is still an order of magnitude slower in the 9-4 steels than in the 4340 alloy.

An analysis was conducted on the influence of applied stress intensity factor on the environmentally-induced crack growth rate. In a given specimen, the applied load is constant, hence the applied stress intensity factor (K_i) increases during the test due to the crack extension. Using resistance measurement data, curves relating crack size to exposure time were constructed for several center notched 4340 specimens (235 Ksi strength level) exposed to a distilled water environment. The slopes of these curves, which represent the instantaneous crack growth rates (da/dt), were graphically determined at several values of crack length and in this manner the relationship between crack growth rate and applied stress intensity factor could be determined. Results obtained on two specimens are presented in Figure 32 along with data published by Johnson and Willner for H-11 steel (9). For any given specimen, the crack growth rate was directly proportional to the applied stress intensity factor , in agreement with conclusions presented by Johnson and Willner. However, the actual value of crack growth rate also varied significantly from specimen to specimen and was not a unique function of the stress intensity parameter, (i.e. compare Specimen 5-147 to 5-162 in Figure 32).

4. Effect of Inhibitors

Sodium dichromate is often used as an inhibitor to decrease the susceptibility of steels to corrosion or stress corrosion. The results of several experiments to determine the effect of sodium dichromate (Na_2CrO_4) on the delayed failure of 4340 notch bend specimens are summarized in Table 5. When these data are compared with the data in Table 9,* it is apparent that dichromate can extend the time to failure by two orders of magnitude at any value of K_i in distilled water, but does not appear to have as significant an effect in 1.5 N and 3.0 N NaCl solutions.

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* See Appendix.

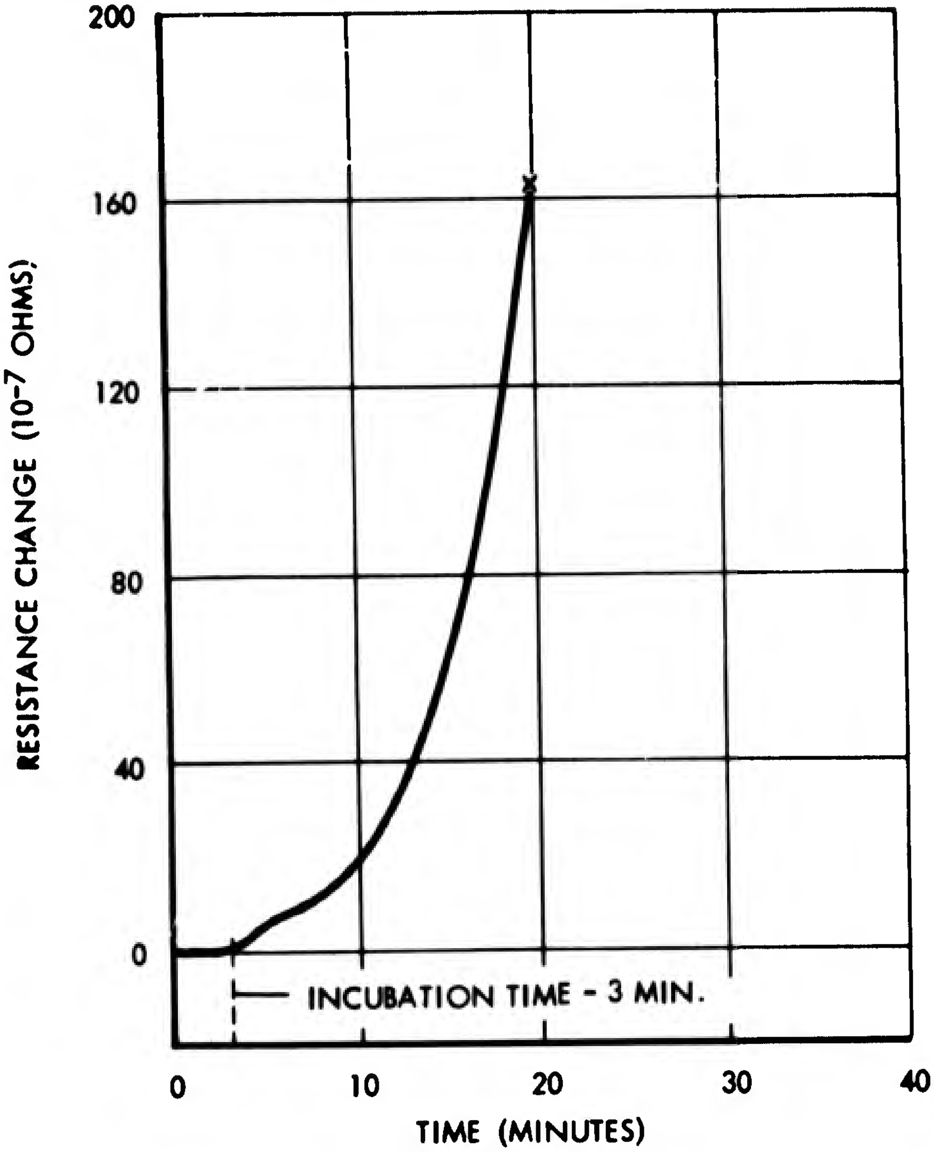

Figure 31. Typical Crack Growth Curve, 4340 Notch Bend Specimen, Distilled Water Environment, 56,100 psi Applied Stress.

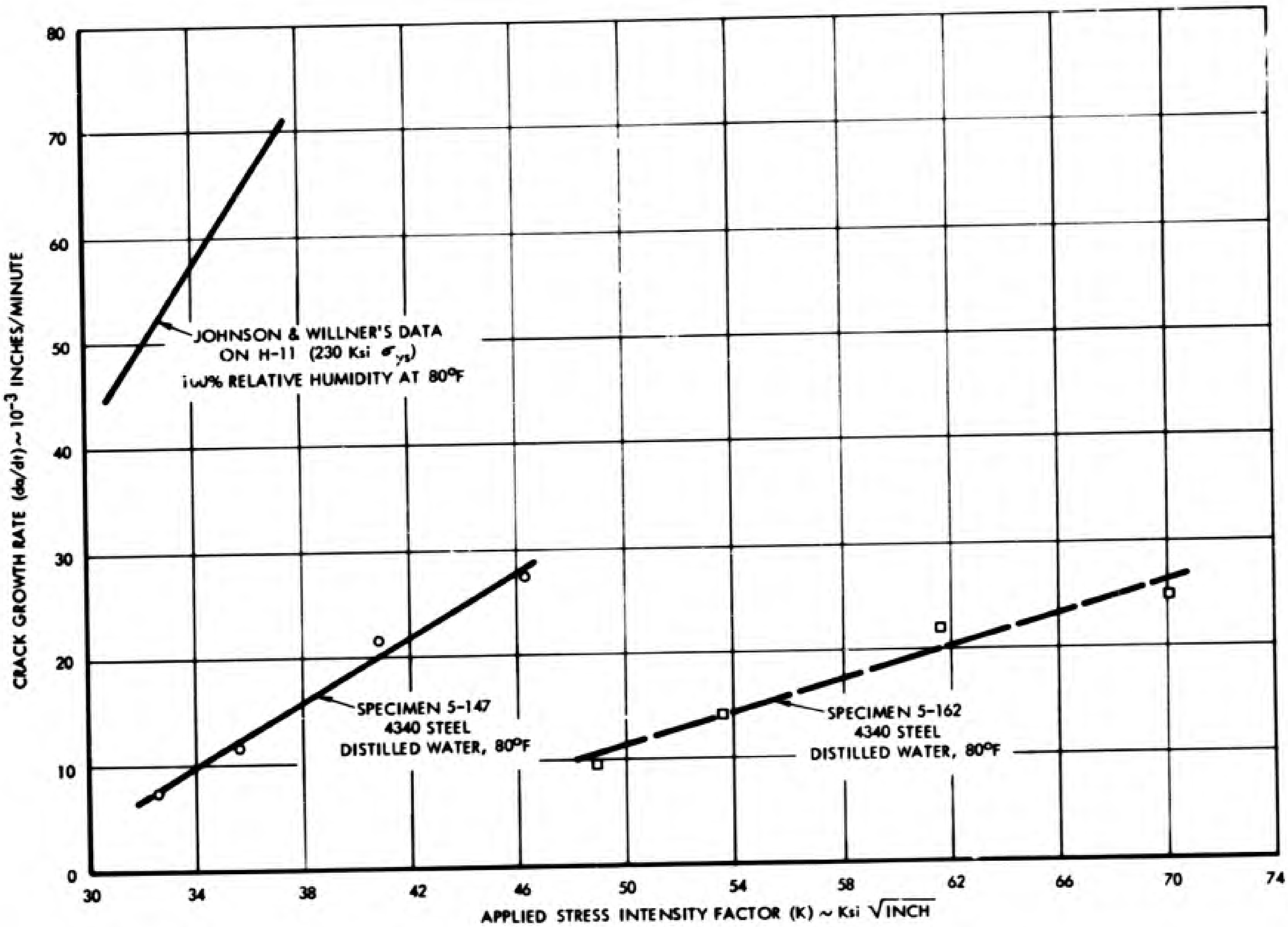

Figure 32. Variation of Crack Growth Rate with Applied Stress Intensity Factor.

TABLE 5

DELAYED FAILURE CHARACTERISTICS OF AISI 4340 STEEL (235 Ksi STRENGTH LEVEL)

CANTILEVER BEAM SPECIMENS, DICHROMATE INHIBITED ENVIRONMENTS

Initial Max. Fiber Stress (Ksi)	Initial Plane Strain Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Failure Time t_f (min.)	Environment	Final Crack Length a_f (inch)	Final Plane Strain Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)	K_i / K_{IC} (K_{IC} = 78.9 Ksi $\sqrt{inch}$)
49.4	61.6	1,770	Distilled H_2O + 0.25% Na_2CrO_4	.519	141.4	.78
42.7	50.1	126	"	.561	147.0	.63
38.2	51.6	654	"	.587	161.8	.65
38.2	40.7	20,022 NF	"	—	—	.52
42.7	47.6	126	1.5N NaCl + 0.25% Na_2CrO_4	.591	165.6	.60
49.4	58.8	142	3.0N NaCl + 0.25% Na_2CrO_4	.578	182.2	.75

Inhibition by dichromate occurs either through stabilization of the surface oxide film or through a reduction of the aggressiveness of the solution. If the former is the active mechanism, crack growth curves should show a considerably extended incubation time and little effect on crack growth rates. If, however, the solution is made less aggressive by the addition of dichromate, both the incubation time and slow crack growth rate should be affected. It appears from the data obtained to date that dichromate acts to stabilize the surface film, since the failure times at lower applied stress intensity (where rupture of the film at the tip of the crack may not be completed upon application of the load) are extended at an increasing rate with decreasing K_i.

5. Effect of Impressed Polarization Potential

Studies of the effect of an externally impressed polarization potential were conducted on 4340 steel (235 Ksi strength level) center notched specimens at 50,000 psi applied stress. The results indicate that no appreciable cathodic protection occurs in either distilled water or 3.0N NaCl solution, see Figure 33. Decreased time to failure caused by hydrogen embrittlement occurred above 100 millivolts in distilled water and above 250 millivolts in 3.0N NaCl solution. Visible hydrogen generation on the specimen surface occurred at about 300 millivolts in both environments. The presence of chlorides appears to retard the stress corrosion process at all levels of impressed polarization potential in the range 200 millivolts anodic to about 600 millivolts cathodic.

The effect of an impressed polarization potential on the delayed failure of HP 9-4-45 steel (242 Ksi strength level) at 120 Ksi applied stress is summarized in Figure 34. Cathodic protection occurred at potentials between 0 and -300 millivolts in both distilled water and 3.0N NaCl solution, while acceleration due to hydrogen embrittlement occurred at larger cathodic potentials. Stress corrosion at an increased rate occurred with the application of an anodic potential. The load bearing area of the specimen tested at +190 mv. in 3.0N NaCl solution was reduced by 26% during the test because of accelerated corrosion at the free surfaces.

The results indicate that the HP 9-4-45 steel behaves according to the classic stress corrosion mechanism which involves anodic dissolution along preferential paths in the metal. Acceleration of the corrosion process occurs when an anodic potential is applied to the specimen/electrolyte system and cathodic protection occurs with relatively small impressed cathodic potentials. As the cathodic potential is increased, liberating more and more hydrogen at the specimen surface due to an electrochemical reaction between the steel and the water, hydrogen embrittlement begins to cause a decrease in failure time.

The 4340 steel, however, does not follow this behavior in either water or 3N NaCl solution. This indicates that a single mechanism, such as hydrogen embrittlement, is responsible for stress corrosion of 4340 at all impressed potentials below +300 millivolts.

The electropotential studies show that two distinct mechanisms - anodic dissolution and hydrogen embrittlement - can operate in the high strength steels depending on the specific steel alloy involved. The role of specific variables, such as impressed potential, environment content, and material composition require additional study to determine the conditions which determine when a specific mechanism becomes operative.

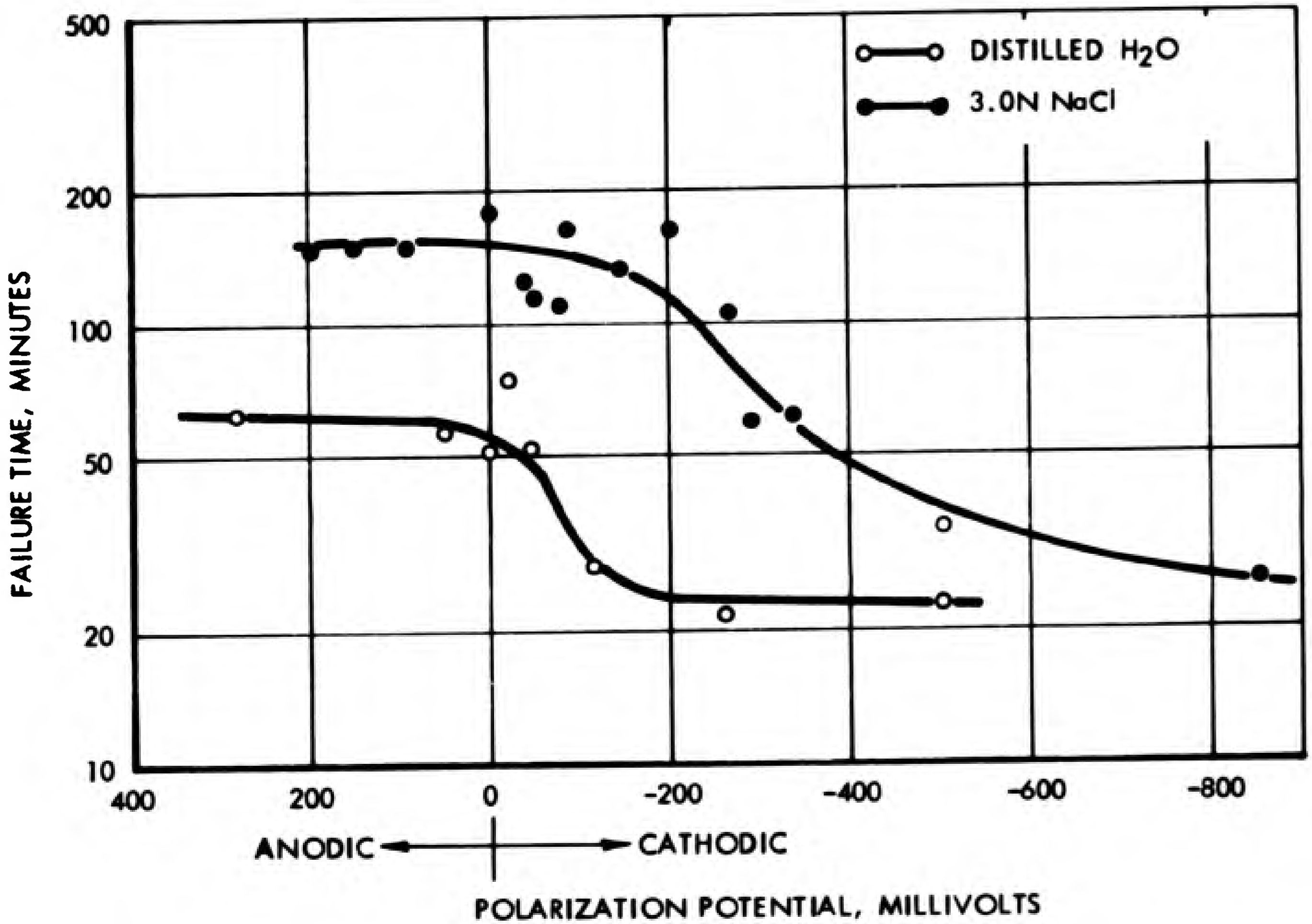

Figure 33. Effect of Impressed Polarization Potential on Delayed Failure of AISI 4340 Steel (235 Ksi Strength Level) Center-Notch Specimens in Distilled Water and 3.0 N NaCl Solution at 50 Ksi Applied Stress.

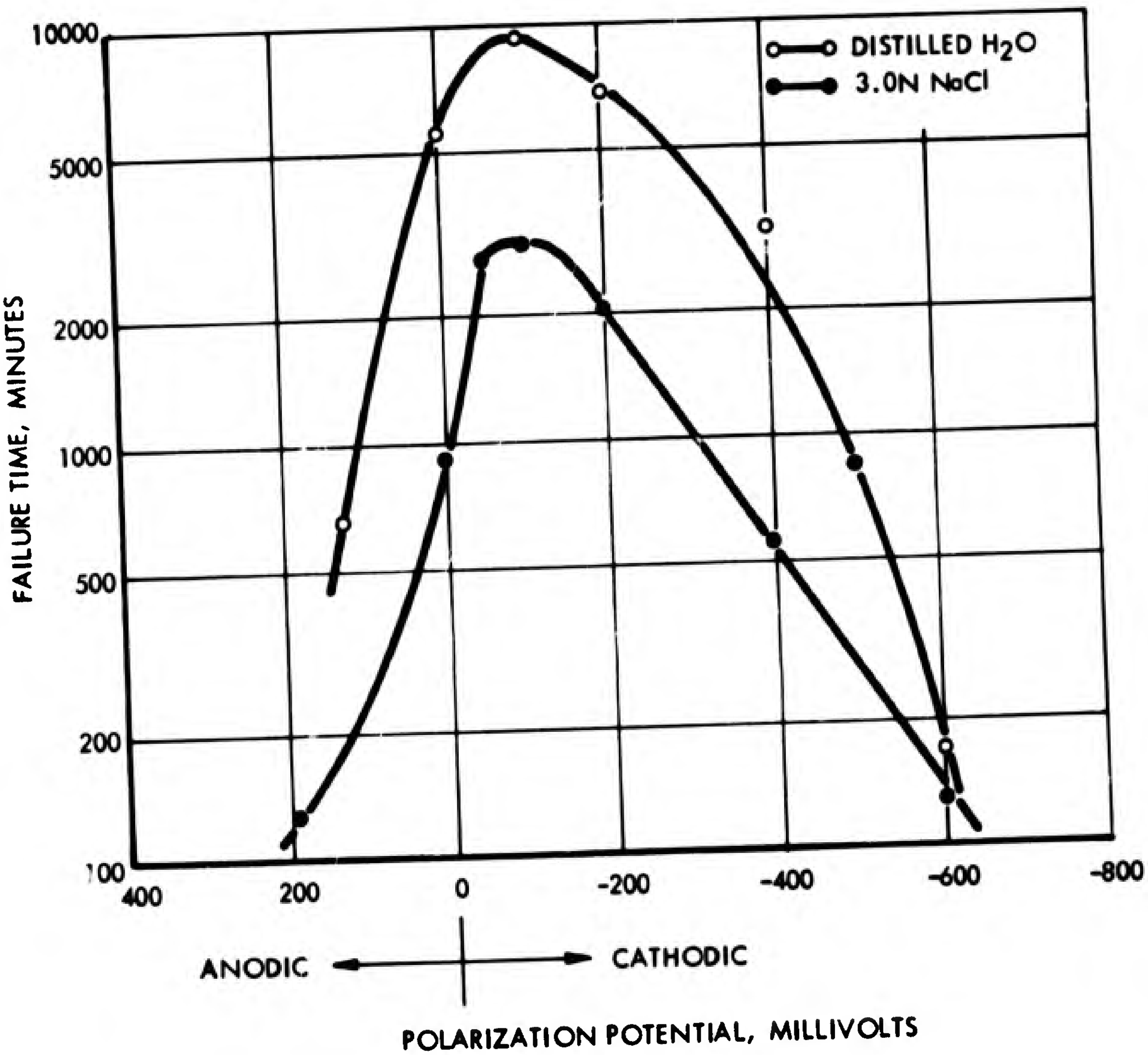

Figure 34. Effect of Impressed Polarization Potential on Delayed Failure of HP 9-4-45 Steel (242 Ksi Strength Level) Center-Notch Specimens in Distilled Water and 3.0 N NaCl Solution at 120 Ksi Applied Stress.

SECTION IV

SUMMARY AND CONCLUSIONS

The delayed failure characteristics of 4340 and HP 9-4-45 steel in distilled water, 1.5N, and 3.0N NaCl environments were evaluated using smooth tensile, precracked tensile, and cantilever beam precracked specimens. Delayed failures occurred in both materials at the 235 to 245 Ksi tensile strength level in all the environments evaluated. The presence of a precrack decreased the failure time by at least three orders of magnitude and extended the stress range over which failure occurred to values as low as 20% of the conventional notch tensile strength measured in air. A comparable stress intensity parameter below which delayed failure did not occur (K_{ISCC}) was defined with both the sheet and beam specimens. At a given stress intensity parameter, the failure times for the beam specimens (plane strain conditions) were less than for the sheet specimens. However, the failure time curves for both specimen types could be normalized when the applied stress was plotted as the ratio of applied stress intensity parameter to the critical stress intensity parameter obtained by testing in air (K_i/K_c). These results indicate that there is no basic difference in the environmentally-induced failure mechanism under plane stress or plane strain conditions.

In the 4340 steel there was a tendency for the distilled water to be more aggressive than the environments containing chlorides. The tests on the HP 9-4-45 steel showed the reverse effect as the failure times were decreased in the smooth sheet precracked sheet, and precracked beam specimens by the chloride additions. The effect of impressed polarization also was different for the two steel types. The application of a cathodic potential on the 4340 steel produced a decrease in the failure times in both distilled water and chloride environments. This behavior was consistent with a hydrogen embrittlement failure mechanism. In the HP 9-4 steels however, the application of a slight cathodic potential produced an increase in failure times (cathodic protection). Further increases in the cathodic potential accelerated the delayed failure process by inducing hydrogen embrittlement. The results obtained on the 9-4 steel indicate that anodic dissolution is the predominant mechanism of stress corrosion in this material.

Crack growth curves were evaluated with particular reference to the factors that control the incubation time which precedes the initiation of slow crack growth. As a result of a series of aging and reversibility studies, the incubation time for 4340 steel was defined as the time required for the environment to permeate a film that is formed at the crack tip subsequent to the precracking operation. By aging under load prior to the application of the environment, the incubation time for 4340 steel could be increased by at least an order of magnitude while aging in the environment prior to applying the load could eliminate the incubation time. Once the crack was initiated, the crack growth rate was independent of the prior loading and aging sequence. On this basis the film formation controlled the incubation behavior but not the crack propagation sequence. The variation in delayed failure susceptibility between the 4340 and 9-4 steels could not be explained solely on the basis of possible differences in incubation time. In the 9-4 steel, the incubation time was not only considerably extended, indicating a more resistant film, but the subsequent crack growth rate was also significantly slower.

The difference in behavior between the 4340 and HP 9-4 steels in terms of reaction to impressed potential and chlorides in solution indicates that general mechanism of delayed failure in aqueous environments may not be applicable to all classes of high strength steels.

A few critical experiments are being run to confirm the concepts of stress corrosion developed during the first year's effort. The second year's program will be concerned primarily with the determination of the effect of metallurgical variables, such as chemical compositions and metallurgical structure, on the delayed failure process in martensitic high strength steels.

REFERENCES

1. G.L. Hanna, A.R. Troiano and E. A. Steigerwald, "Mechanism for the Embrittlement of High Strength Steels by Aqueous Environment", ASM Trans. Quarterly, 57, No.3, 658, (September 1964), Also Air Force Report RTD-TDR-63-4225.

2. B. F. Brown, "Notch Sensitivity Effects in Stress Corrosion and Hydrogen Embrittlement Tests on High Strength Steels", Corrosion, 15, 3998, (August 1959).

3. "Fracture Testing of High Strength Sheet Materials", Report of Special ASTM Bulletin 18, (January 1960).

4. W. J. Barnett and A.R. Troiano, "Crack Propagation in Hydrogen Induced Brittle Fracture of Steel", Trans. AIME, 209, 486, (1959).

5. E. A. Steigerwald and G. L. Hanna, "Initiation of Slow Crack Propagation in High Strength Materials", Proc. ASTM, 62, 885, (1962).

6. W. F. Brown, Jr. and J. E. Srawley, "Current Status of Plane Crack Toughness Testing", NASA TM X-52209, June 29, 1966.

7. J. E. Srawley and W. F. Brown, Jr., "Fracture Toughness Testing Methods" in ASTM Special Technical Publication No. 381, Fracture Toughness Testing and Its Applications, ASTM, Philadelphia, Pa., April 1965, pp 180 ff.

8. C. D. Beachem and B. F. Brown, "A Comparison of Three Specimens for Evaluating the Susceptibility of High Strength Steel to Stress Corrosion Cracking", to be published as NRL Report, (1966).

9. H. H. Johnson and A. M. Willner, "Moisture and Stable Crack Growth in a High Strength Steel", App. Mat'ls. Research, January 1965.

APPENDIX

TABULATED SUMMARIES

OF

DELAYED FAILURE DATA

TABLE 5

DELAYED FAILURE CHARACTERISTICS OF AISI 4340 STEEL
(235 Ksi Strength Level) PRECRACKED SHEET SPECIMENS

Applied Stress σ_a (Ksi)	σ_a / σ_{NTS}, σ_{NTS} = 164.4 Ksi	Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Incubation Time, t_i (min.)	Failure Time, t_f (min.)	Environment, pH	Final Crack Length, 2 a_f (inches)	Total Resistance Change (10^{-6} ohms)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{\text{inch}}$)	K_i / K_{cf}
Distilled Water									
165.7	1.01	123.8	0	1.5	4.5	—	750	—	—
162.0	.99	120.5	0	38	4.5	0.90	63	149.4	.81
151.3	.92	111.8	0	14.8	4.5	0.96	235	143.5	.78
139.0	.84	102.6	NR	104	4.5	1.07	NR	143.0	.72
120.4	.73	88.4	NR	66	4.5	1.24	NR	140.2	.63
118.4	.72	87.4	NR	~75	4.5	1.28	NR	144.8	.60
100.3	.61	73.2	14	103	4.5	1.32	722	126.7	.58
80.5	.52	57.5	4	111	4.5	1.37	936	106.5	.54
60.6	.37	43.0	NR	38.4	4.5	1.46	NR	88.1	.49
59.8	.36	43.1	12	95	4.5	1.59	1107	101.2	.43
50.4	.31	36.4	275	1476	4.5	1.7	—	99.3	.36
39.8	.24	28.8	0	108	4.5	1.69	1236	74.8	.39
30.0	.18	20.5	NR	14,425NF	4.5	—	NR	—	(.20)
20.0	.12	12.7	NR	11,570NF	4.5	—	NR	—	(.13)
1.5N NaCl Aqueous Solution									
162.5	.99	120.9	0	36.3	4.5	0.91	190	150.1	.80
160.5	.98	119.2	3	36.3	4.5	0.92	118	149.1	.80
139.8	.85	103.3	NR	72	4.5	1.14	NR	154.9	.67
119.0	.72	87.3	0	82.6	4.0	1.20	621	137.9	.62
101.2	.62	71.7	NR	18	4.0	1.28	NR	124.7	.58
79.8	.48	57.7	1.3	105.6	4.5	1.52	1125	125.4	.46
60.6	.37	43.4	3.0	146.4	4.5	1.60	1247	103.7	.42
40.1	.24	28.8	4.0	280.8	4.0	1.76	2015	89.2	.32
30.0	.18	21.5	NR	2590	4.5	1.66	NR	54.6	.39

* NF - Indicates no failure
* NR - Indicates value not recorded

TABLE 6 (Cont'd)

Applied Stress σ_a (Ksi)	σ_a/σ_{NTS} σ_{NTS} = 164.4 Ksi	Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Incubation Time, t_i (min.)	Failure Time, t_f (min.)	Environment, pH	Final Crack Length, 2 a_f (inches)	Total Resistance Change (10^{-6} ohms)	Final Plane Stress, Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)	K_i/K_{cf}
3.0N NaCl Aqueous Solution									
159.9	.97	118.4	0	45.4	4.5	0.90	253	148.3	.80
141.8	.86	104.6	7	92.5	4.5	1.07	318	145.3	.72
120.7	.73	88.5	3	83	4.5	1.30	500	151.5	.58
100.9	.61	73.7	12	135	4.5	1.35	655	130.8	.56
79.7	.48	57.5	0	127	4.5	1.49	1087	121.0	.48
60.2	.37	42.6	9	142	4.5	1.62	1121	116.0	.37
40.0	.24	28.8	40	239.5	4.5	1.78	1647	91.9	.31
39.3	.23	28.2	0	>150	4.5	—	>255	—	(.26)

* NF - Indicates no failure
* NR - Indicates value not recorded

TABLE 7

DELAYED FAILURE CHARACTERISTICS OF AISI 4340 STEEL
(207 Ksi Strength Level) PRECRACKED SHEET SPECIMENS

Applied Stress σ_a (Ksi)	σ_a/σ_{NTS} (σ_{NTS} = 168.7 Ksi)	Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Incubation Time, t_i (min.)	Failure Time, t_f (min.)	Environment pH	Final Crack Length, $2a_f$ (inches)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)
Distilled Water							
161.2	.96	120.2	NR*	27:95	4.5	0.85	142.6
119.8	.71	87.8	NR	1392	4.5	1.13	131.4
99.3	.59	72.0	NR	1998	4.5	1.22	116.8
80.7	.48	58.5	NR	2422	4.5	1.06	81.1
59.2	.35	42.7	NR	2236	4.5	1.53	92.3
49.2	.29	36.0	NR	890	4.5	1.67	80.3
40.0	.24	28.9	NR	6768	4.5	1.56	75.3
1.5N NaCl Aqueous Solution							
141.5			15	381	4.5		
120.9	.75	88.5	NR	4004	4.5	0.85	105.0
105.4	.63	73.4	NR	2184	4.5	1.1	106.0
80.4	.48	58.1	NR	2136	4.5	1.32	102.0
60.1	.36	43.2	NR	1886	4.5	1.51	92.5
50.4	.30	36.3	NR	3084	4.5	1.58	83.3
40.2	.24	28.0	NR	11,082NF**	4.5	0.648	28.0
3.0N NaCl Aqueous Solution							
100.6	.60	73.4	NR	3285	4.5	1.12	106.2
100.5	.60	73.2	NR	2568	4.5	1.18	112.5
79.4	.47	57.6	NR	1572	4.5	1.17	87.8
70.4	.42	50.9	NR	2233	4.5	1.34	89.4
59.9	.36	43.2	NR	1554	4.5	1.52	92.2
49.9	.30	35.5	NR	2530	4.5	1.62	87.5
40.1	.24	29.4	NR	14,330NF	4.5	No SCG	29.4

* NR - Indicates value not recorded
** NF - Indicates no failure

TABLE 8

DELAYED FAILURE CHARACTERISTICS OF 4340 STEEL
(235 Ksi Strength Level) CANTILEVER BEAM SPECIMENS (Series A)

Initial Max. Fiber Stress (Ksi)	Initial Plane Strain Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Failure Time (min.)	Final Crack Length, a_f (inch)	Final Plane Strain Stress Intensity, K_{cf} (Ksi inch)	K_i/K_{IC} (K_{IC} = 76.4 Ksi $\sqrt{\text{inch}}$)
Distilled Water, pH 4.5					
42.7	71.3	8	0.413	96.5	0.93
38.2	62.2	9.5	0.581	45.0	0.81
33.8	57.0	9.5	0.657	167.3	0.75
29.3	47.8	18	0.809	112.6	0.63
24.8	40.9	11.2	0.664	134.4	0.54
20.3	30.8	1938	0.745	105.9	0.41
1.5N NaCl Aqueous Solution, pH 4.5					
42.7	71.6	20	0.499	129.8	0.94
38.2	65.2	21.3	0.536	121.3	0.85
33.8	53.9	44	0.579	127.4	0.71
29.3	50.7	54	0.599	117.6	0.66
24.8	41.2	60	0.654	124.5	0.54
24.8	38.2	84	0.684	142.4	0.50
20.3	26.1	228	0.893	38.0	0.34
3.0N NaCl Aqueous Solution, pH 4.5					
42.7	71.8	0.2	0.313	71.8	0.94
38.2	61.8	38.9	0.560	131.8	0.81
33.8	54.8	28.4	0.519	101.4	0.72
29.3	49.1	48	0.662	152.8	0.64
24.8	42.0	78	0.655	125.7	0.53
20.3	22.4	18,036	0.995		0.29

TABLE 9

DELAYED FAILURE CHARACTERISTICS OF 4340 STEEL
(235 Ksi Strength Level) CANTILEVER BEAM SPECIMENS (Series B)

Initial Max. Fiber Stress (Ksi)	Initial Plane Strain Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Incubation Time (min.)	Failure Time (min.)	Final Crack Length (inch)	Final Stress Intensity K_{cf} (Ksi $\sqrt{\text{In}}$)	K_i/K_{IC} (K_{IC} = 78.9 Ksi $\sqrt{\text{inch}}$)
Distilled Water, pH 4.5						
59.5	66.0	2	21.5	.520	187.7	.84
56.1	70.4	126	180	.546	188.4	.89
56.1	69.9	3	20	.497	160.8	.88
49.4	59.2	1	27.1	.575	183.2	.75
42.7	53.4	1	29.5	.850	763.3	.68
42.7	51.5	—	35.0	.603	180.1	.65
38.2	47.5	2	30.1	.638	178.2	.60
33.7	44.6	>435	435 NF	*	—	.57
33.7	41.5	—	187	.470	87.7	.525
29.3	37.5	1	29.5	.754	242.9	.48
29.3	34.8	9	31.8	.644	140.2	.44
1.5N NaCl Aqueous Solution, pH 4.5						
33.7	43.9	—	127	.593	133.1	.56
29.3	36.0	—	480	.688	171.9	.46
3.0N NaCl Aqueous Solution, pH 4.5						
42.7	50.9	—	126	.583	161.9	.65
33.7	41.1	—	117	.675	184.9	.52
29.3	34.5	—	124	.604	117.8	.44
24.8	40.6	—	18,000NF	*	—	.52

* No Apparent Slow Crack Growth

TABLE 10

DELAYED FAILURE CHARACTERISTICS OF HP 9-4-45 STEEL
(242 Ksi Strength Level) CENTER NOTCH SPECIMENS

Applied Stress, σ_a (Ksi)	σ_a / σ_{NTS} (σ_{NTS} = 162.4 Ksi)	Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Failure Time, t_f (minutes)	Final Crack Length, $2a_f$ (inches)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)	K_i / K_c (K_c = 119.7 Ksi $\sqrt{in.}$)
Distilled Water, pH 4.5						
159.1	.98	110.4	.1	—	—	.92
155.6	.96	107.8	.57	—	—	.90
151.1	.92	104.7	.84	—	—	.87
149.5	.92	103.4	1047	—	—	.86
146.3	.90	101.1	.48	—	—	[illegible]
145.0	.89	100.2	920	—	—	.84
140.7	.87	97.0	795	—	—	.81
139.5	.86	96.2	1610	—	—	.80
133.3	.82	91.7	5774	0.889	110.6	.77
131.4	.81	90.2	2436	0.889	111.8	.75
119.8	.74	81.9	415	0.710	88.2	.68
118.5	.73	81.2	5585			.68
110.7	.68	75.7	4231	0.851	90.6	.64
105.6	.65	72.1	6550	1.344	151.5	.60
101.0	.62	68.9	7674	0.940	189.6	.58
95.7	.58	65.1	5110	1.331	132.2	.54
89.8	.55	61.0	8833	1.178	102.2	.51
83.6	.52	56.9	7478	.806	65.6	.48
80.8	.50	50.5	8445	.787	62.2	.42
67.3	.41	45.5	10890	1.120	73.6	.38
1.5N NaCl Aqueous Solution, pH 4.5						
149.2	.92	103.0	322	0.729	110.1	.86
141.3	.87	97.3	460	0.895	121.7	.81
131.0	.81	90.0	542	0.961	120.3	.75
127.8	.79	87.7	1542	1.008	123.5	.73
123.3	.76	84.5	2101	1.253	153.8	.71
109.9	.68	75.1	1568	1.070	112.1	.63
94.7	.58	69.5	2131	1.110	99.6	.54

TABLE 10 (Continued)

Applied Stress, σ_a (Ksi)	σ_a / σ_{NTS} (σ_{NTS} = 162.4 Ksi)	Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Failure Time, t_f (minutes)	Final Crack Length, $2a_f$ (inches)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)	K_i / K_c (K_c = 119.7 Ksi $\sqrt{in.}$)
3.0N NaCl Aqueous Solution, pH 4.5						
149.5	.92	103.4	1.9	—	—	.86
147.2	.91	101.7	96.2	—	—	.85
144.1	.89	99.5	89.4	—	—	.83
139.2	.86	95.8	726	0.712	103.1	.80
136.8	.84	94.3	300	0.863	111.8	.79
117.4	.72	80.3	906	0.856	100.2	.67
108.0	.66	73.7	3607	0.869	91.2	.62
102.1	.63	69.8	32,920 NF	0.739	73.0	.58
94.7	.58	64.6	4314	.961	86.4	.54
89.3	.55	60.8	5502	1.075	91.8	.51
67.8	.42	45.9	13,578	1.199	79.6	.38
58.9	.36	40.0	6479	1.324	76.7	.32

TABLE 11

SUMMARY OF DELAYED FAILURE OF HP 9-4-45 STEEL
(242 Ksi Strength Level) CANTILEVER BEAM SPECIMENS

Initial Max. Fiber Stress (Ksi)	Initial Plane Strain Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Failure Time (minutes)	Final Crack Length (inches)	Final [redacted] Strain Stress Intensity, K_{cf} (Ksi $\sqrt{\text{inch}}$)	K_i / K_{IC} (K_{IC} = 68.0 Ksi $\sqrt{\text{inch}}$)
Distilled Water, pH 4.5					
50.5	67.2	105	—	—	.99
49.4	65.0	1,310	—	—	.96
42.7	60.9	425	.283	80.5	.90
42.7	57.5	1,960	—	—	.85
38.2	56.8	870	—	—	.84
38.2	45.7	17,334 NF	—	—	.67
36.0	34.0	474	.477	128.5	.79
36.0	52.6	756	.425	92.8	.77
33.7	49.0	3,822	.417	95.5	.72
29.1	42.8	570	.546	141.7	.63
29.1	28.0	18,600 NF	—	—	.41
28.1	39.8	648	.527	127.3	.59
24.8	36.1	636	.547	121.4	.53
1.5N NaCl Aqueous Solution, pH 4.5					
49.4	51.4	1,080	.359	125.6	.76
44.9	66.4	270	—	—	.98
44.9	64.8	3	—	—	.95
44.9	53.4	990	.304	88.3	.78
42.7	59.9	1,026	.315	90.3	.88
42.7	51.2	1,254	.418	120.7	.75
40.5	57.3	1,121	.298	79.7	.84
40.5	48.9	14,430 NF	—	—	.72
38.2	46.9	780	.346	88.9	.69
36.0	52.8	882	.365	88.3	.78

TABLE 11 (Continued)

Initial Max. Fiber Stress (Ksi)	Initial Plane Strain Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Failure Time (minutes)	Final Crack Length (inches)	Final Plane Strain Stress Intensity, K_{cf} (Ksi $\sqrt{\text{inch}}$)	K_i/K_{IC} (K_{IC} = 68.0 Ksi $\sqrt{\text{inch}}$)
3.0N NaCl Aqueous Solution, pH 4.5					
53.0	67.7	1	—	—	.995
51.6	62.2	930	.219	83.7	.91
50.5	56.6	648	.244	84.7	.83
49.4	60.1	1584	.293	100.0	.88
47.1	57.7	984	.239	77.8	.85
44.9	65.5	10	—	—	.96
44.9	63.3	172	—	—	.93
44.9	62.1	1374	.301	89.2	.91
42.7	50.5	1620	.226	68.2	.74
40.5	62.0	1530	.314	93.1	.91
40.5	51.6	636	.256	72.1	.76
40.5	45.0	14,376 NF	—	—	.66
39.3	56.7	660	.405	111.4	.83
38.2	49.9	1116	.334	83.6	.73
38.2	47.4	21,468 NF	—	—	.70
33.7	49.3	564	.369	85.1	.73
33.7	40.9	2830	.263	59.7	.60
29.1	42.6	924	.474	102.8	.63
28.1	42.7	942	.395	81.1	.63

TABLE 12

DELAYED FAILURE OF AISI 4340 STEEL (235 Ksi STRENGTH LEVEL) CENTER NOTCH SPECIMENS. POLARIZATION STUDIES IN DISTILLED WATER AT 50 Ksi APPLIED STRESS

Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Polarizing Potential; (V_I - V_N) (millivolts)	Failure Time t_f (min.)	Final Crack Length (2 a_f)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)
36.2	+280	62.4	1.6715	93.1
43.2	+50	56.4	1.6512	108.4
36.1	0	51.0	1.5233	76.1
36.1	-20	74.4	1.5705	89.5
36.0	-44	51.6	1.3266	62.0
36.6	-117	28.2	1.6915	91.1
35.2	-260	21.6	1.5013	80.3
36.3	-500	22.8	1.6449	89.5
36.1	-500	34.8	1.3305	62.7

TABLE 13

DELAYED FAILURE OF AISI 4340 STEEL (235 Ksi STRENGTH LEVEL) CENTER NOTCH SPECIMENS. POLARIZATION STUDIES IN 3.0N NaCl AQUEOUS SOLUTION AT 50 Ksi APPLIED STRESS

Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{inch}$)	Polarizing Potential; $(V_I - V_N)$ (millivolts)	Failure Time t_f (min)	Final Crack Length $(2\ a_f)$	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{inch}$)
36.0	+200	147.0	1.589	83.0
—	+150	149.4	1.537	—
36.2	+90	150.6	1.602	85.1
36.3	0	180.0	1.631	89.1
36.2	-40	122.4	1.635	89.4
36.2	-49	116.4	1.697	98.4
35.9	-54	141.0	1.669	92.3
36.4	-79	109.2	1.650	90.5
36.0	-90	162.6	1.530	77.7
35.6	-145	133.2	1.650	90.1
36.2	-264	104.4	1.658	92.4
36.3	-290	59.4	1.601	84.1
36.1	-337	61.5	1.539	78.4
36.1	-854	25.8	1.706	102.1

TABLE 14

DELAYED FAILURE OF HP 9-4-45 STEEL (242 Ksi Strength Level) CENTER NOTCH SPECIMENS. POLARIZATION STUDIES IN DISTILLED WATER AT 120 KSI APPLIED STRESS

Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Polarizing Potential; $(V_I - V_N)$ (millivolts)	Failure Time t_f (minutes)	Final Crack Length $2a_f$	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{\text{inch}}$)
81.4	+130	643	.955	110.8
81.2	0	5585	—	—
78.8	-100	9424	.792	92.9
79.6	-200	6847	.816	95.7
82.7	-400	3154	.707	90.2
82.1	-600	170	1.089	124.0

TABLE 15

DELAYED FAILURE OF HP 9-4-45 STEEL(242 Ksi Strength Level) CENTER NOTCH SPECIMENS, POLARIZATION STUDIES IN 3.0N NaCl AQUEOUS SOLUTION AT 120 Ksi APPLIED STRESS

Initial Plane Stress Stress Intensity, K_i (Ksi $\sqrt{\text{inch}}$)	Polarizing Potential; ($V_I - V_N$ (millivolts)	Failure Time t_f (minutes)	Final Crack Length, $2a_f$ (inches)	Initial Cross-Sectional Area, A_i (sq. inch)	Cross-Sectional Area, A_{i2} (sq. inch)	Final Plane Stress Stress Intensity, K_{cf} (Ksi $\sqrt{\text{inch}}$)
79.9	+190	126	0.689	0.0548	0.0404	114.8
80.3	0	906	0.856	0.0586	—	100.2
79.9	-50	2733	0.892	0.0540	—	99.9
81.9	-100	2998	1.084	0.0529	—	124.4
81.5	-200	2047	1.070	0.0531	—	120.2
82.7	-397	553	1.094	0.0567	—	126.2
82.6	-500	843	1.107	0.0527	—	—
81.7	-596	130	1.194	0.0541	—	142.3

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13. ABSTRACT Delayed failures of martensitic high-strength steels in aqueous environments were studied to determine the effect of environmental and metallurgical variables on the mechanisms of stress corrosion. The effects of chloride content, specimen geometry, and polarization potential on the delayed failure of AISI 4340 (235 and 207 Ksi strength level) and HP 9-4-45 (242 Ksi strength level) steels were evaluated. Incubation time for slow crack growth and crack growth rates were measured at various combinations of applied stress and environment using change of resistance and compliance measurements on precracked center-notch tensile and cantilever loaded notch bend specimens.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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